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TEXT-BOOK OF PETROLOGY

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CONTAINING

A SUMMARY OF THE MODERN THEORIES OF PETROGENESIS, A DESCRIPTION OF THE ROCK-FORMING MINERALS, AND A SYNOPSIS OF THE CHIEF TYPES OF THE IGNEOUS ROCKS AND THEIR DISTRIBUTION AS ILLUSTRATED BY THE BRITISH ISLES

BY

F. H. HATCH, PH.D.

SIXTH EDITION—REVISED

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PREFACE TO THE SIXTH EDITION.

In this edition, besides the correction of a few typographical errors and of some misspellings of place-names, there are several small improvements suggested by friends. Especially to be noted is a simplification, but without alteration of principle, of the tables of classification of the Plutonic and of the Volcanic Rocks (on pages 153 and 248). A new map, showing the volcanic area of Glencoe and the Etive granite complex, has also been added (on page 371) by kind permission of Messrs. Clough, Maufe and Bailey, and of the Council of the Geological Society. Mr. Pringle has revised the Index.

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PREFACE TO THE FIFTH EDITION.

Although reprinted in 1903 and again in 1905, this book has not been revised since 1892. During the sixteen years that have elapsed since that date, Petrology has advanced so rapidly that to bring the book up-to-date has meant practically re-writing it. In doing this, my endeavour has been to retain as far as possible the general arrangement of the Edition of 1892, which I believe has been found useful both by students and by those engaged in teaching. Among new features of the present Edition are fuller references to literature, more complete lists of chemical analyses, and the separation of the part treating of the classification of rock types from that dealing with their distribution as illustrated by the British Isles. Many new cuts have also been added.

The task of bringing the book up to the requirements of modern Petrology has been considerably lightened by the very great assistance I have received from many friends. My thanks are particularly due to Mr. R. H. Rastall, Fellow of Christ's College, Cambridge, for much valuable help. It was at his instigation I undertook the revision; and he has been kind enough to read the proofs and to supply many new micro-photographs (mainly of sections in the Students' Series of the Sedgwick Museum in Cambridge). I have also to thank Mr. George Barrow for valuable information regarding the distribution of the Granites of the Central Highlands, Dr. Flett for reading through some of the parts dealing with the work of the Geological Survey, Messrs. J. Romanes and E. S. Gandy for a careful verification of the physical constants in Chapter III of Part II, and Mr. A. Pringle for reading the proofs and supplying a very full index, which has added very considerably to the value of the book.

For the use of blocks I am indebted to Professor W. C. Brögger, Dr. J. E. Marr, Messrs. A. Harker and G. J. Williams, and the Director of the Geological Survey; also to the Council of the Geological Society and the Controller of H.M. Stationery Office for permission to reproduce cuts that have appeared in the Quarterly Journal and in the publications of the Geological Survey, respectively. At the end of the book is appended a "Table for the determination of the chief Minerals of Igneous Rocks in thin section," by Messrs. R. H. Rastall and J. Romanes, which will be very useful to beginners in Petrology.

F. H. HATCH.

Jan. 1*st*, 1909.

PREFACE TO THE SECOND EDITION.

I HAVE taken advantage of the opportunity offered by the exhaustion of the first edition of my "Introduction to Petrology" to thoroughly revise the book, while largely increasing its scope. I have been encouraged to do this both by the favourable notices the book has received from its reviewers and the kind hints proffered me by numerous friends. For valuable suggestions and assistance I have specially to thank the following gentlemen:—Professors T. G. Bonney and J. W. Judd and Messrs. G. Barrow, A. Harker, J. Hort Player, J. J. H. Teall, and W. W. Watts. Mr. Pringle has again been kind enough to revise the proofs.

I have also to acknowledge my indebtedness to Mr. Hinman's *Eclectic Physical Geography* (American Book Co., New York) for the three illustrations forming figures 2, 5 and 6 of my book.[1]

F. H. HATCH.

July 15th, 1892.

PREFACE TO THE FIRST EDITION.

A LITTLE book that should briefly describe the mineral constituents and internal structures of the Igneous Rocks, their mode of occurrence at the surface and their origin beneath the crust of the earth, has long

[1] Being figures 4, 5 and 9 of the fifth edition.

been a *desideratum* among English text-books of Science.

With the view of filling this gap this treatise has been prepared; and it is hoped that it will be found useful, not only as an introduction to the subject, but also as a handy work of reference.

Von Lasaulx's *Einleitung in die Petrographie* served me as a model in the first instance; but in working out my scheme I have thought it desirable to deviate considerably from the arrangement adopted in that excellent little book. In the verification of data Rosenbusch's *Mikroskopische Physiographie* (2 vols.), Fouqué and Lévy's *Minéralogie Micrographique*, Lévy and Lacroix's *Les Minéraux des Roches* and Teall's *British Petrography* have been of great assistance to me; and the illustrations are, in many cases, taken from these works. I have also to thank the Council of the Geological Society and the Editor of the Geological Magazine for permission to reproduce illustrations that have appeared in their journals. The work has profited much by a careful revision of the proof sheets kindly undertaken by Mr. A. Pringle, M.A., B.Sc., of the Museum of Practical Geology, London.

F. H. HATCH.

Nov., 1890.
28 Jermyn Street,
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PETROLOGY.

INTRODUCTION.

Petrology is that department of geological science which has for its object the investigation of the characters and relations of rocks, that is to say, of the various materials of which the earth's crust is built up. **A rock** may be defined as a mineral aggregate, possessing a more or less persistent geological character. In studying rocks, therefore, we have three points of departure: (1) geological character, or mode of occurrence; (2) the nature of the constituent minerals; and (3) the manner of aggregation of the constituent minerals, or rock-texture.

In classifying rocks we must allow each of these factors its proper value. The exclusive use f one of them would lead to incongruous results. Two or more rocks, for example, may be composed of the same minerals and yet have originated in totally dissimilar ways, the result being a difference both

in texture and in mode of occurrence. Thus, a granite, a felspathic grit and a gneiss may all three be composed of quartz, felspar and mica; but in texture and in mode of origin they differ widely. The granite has been produced by the consolidation of a molten magma at some considerable depth beneath the surface: hence it possesses a coarse-grained, highly crystalline texture. The grit, on the other hand, is composed of fragments of minerals that have been derived by disintegration from other rocks, and have been transported and deposited by the agency of moving water. Lastly, in gneiss there is a banded structure, which in most cases has been produced by a re-arrangement of the minerals since the first formation of the rock.[1]

The three rocks made use of in our example may be taken as types of the three classes into which rocks are often divided; viz., **Igneous**, **Sedimentary** and **Metamorphic**.

Since the metamorphic division comprises rocks both of igneous (ortho-gneisses) and of aqueous origin (para-gneisses) a two-fold division of rocks would be more logical. Such a division is not practicable, because the original character of a rock is too often obscured by the secondary structures imposed

1 The banding of some rocks commonly classed as gneisses, however, took place before final consolidation, and is comparable to "fluxion-structure" in lavas. (See page 49.)

by metamorphism. But it may be pointed out that, according to an estimate of F. W. Clarke,[1] the crust of the earth is composed of rocks originally igneous, to the extent of 95 per cent., the remaining 5 per cent. being made up of 4 per cent. of shales, ·75 per cent. of sandstones, and ·25 per cent. of limestones.

In the following pages it is proposed to discuss briefly the origin, characters and distribution of the chief igneous rocks.

[1] *Proc. of the Amer. Phil. Soc.*, vol. xlv., 1906, p. 21.

PART I.

THE PHYSICAL CHARACTERS OF THE IGNEOUS ROCKS.

CHAPTER I.

MODE OF OCCURRENCE.

THE Igneous Rocks are those that have been formed by the consolidation of molten material. We have good reason for believing that the temperature of the interior of the earth is very high—high enough, indeed, to melt all rocks with which we are acquainted at the surface. Physical and mathematical considerations, however, militate against the view that any large proportion of the earth's interior is occupied by liquid matter. It has been customary, therefore, to assume that at great depths the constituents of the globe, although existing at a high temperature, are maintained in the solid form by the enormous pressure to which they are subject at such depths.

A different hypothesis has been advanced by Arrhenius.[1] Since it has been shown experimentally by Tammann[2] that at very high pressures the melting point of solids can be no longer raised by

[1] Arrhenius : Zur Physik des Vulcanismus, *Geologiska Föreningens i Stockholm Förhandlingar*, Band xxii. (1900), p. 395. For a useful summary of Arrhenius' Theory by R. H. Rastall, see *Geol. Mag.* for April, 1907, p. 173.

[2] Tammann : Kristallisieren und Schmelzen, 1903, p. 184.

increasing the pressure, it appears that at great depths the matter composing the earth's interior must be in the gaseous state; for pressure can no longer keep it solid, or even liquid, by raising the melting point. These considerations lead to the hypothesis that below the solid crust of the earth lies a liquid zone, and that beneath this there is a gaseous material which from its high density probably consists largely of iron. The physical properties of gaseous matter under such conditions must be very unlike those associated with gases at the surface of the earth; *inter alia* it would appear to possess high rigidity and low compressibility. It is further calculated that about 80 per cent. of the earth's interior is occupied by gaseous metal (probably iron), 15 per cent. by gaseous rock-magma, and 4 per cent. by liquid magma, leaving 1 per cent. for the solid crust.

The discussion of this question need not detain us. For, whether the portion of the earth immediately beneath the crust is occupied by rock in the molten condition, or by solid material at a sufficiently high temperature to become liquid under a diminished pressure, the ultimate result is the same: if, by one means or another, the external pressure be overcome, liquid magma will move in the direction of least resistance. According to the nature of the resistance presented by the environment, the molten rock will pierce the solid crust of the earth to a greater or less distance; perhaps ultimately reaching the surface, where it will flow out in the form of lava, or be reduced by the violence of the explosion to cinders or to fine ash.

This consideration leads to a two-fold division of igneous rocks; namely, into those that consolidate in large masses at considerable depths beneath the surface, and those that penetrate to upper portions of the crust and are poured out upon the surface. The former are termed **plutonic**, **deep-seated** or **abyssal**, the latter, **volcanic**. The different conditions under which plutonic and volcanic rocks consolidate, are the cause of considerable differences in structure. In the one case, the solidification of the magma under the conditions imposed by a slow rate of cooling, considerable pressure and the presence of occluded water, produces a highly crystalline and coarse-grained texture; while the rapid hardening of a lava, chilled by being spread over a large area of cold rock, and subject, moreover, to diminished pressure and consequent loss of water, imparts to it a more or less vitreous character. Granite and rhyolite—rocks of similar chemical and mineralogical composition—illustrate this difference. The former is wholly crystalline, its large crystals completely filling space to the exclusion of all interstitial matter; while in the latter the crystals are embedded in a glassy or semi-vitreous paste, the streaky character of which evidences the differential movements of the once viscous lava.

Volcanic rocks are, however, connected with their deep-seated or plutonic roots by necks and pipes, or by dykes. The plutonic masses also send off tongues or apophyses into the surrounding rocks, and in some cases even the superficial strata are pierced by dykes and sheets of igneous material that have found no

actual outlet. A third division of igneous rocks is therefore necessary to embrace these connecting links between plutonic and volcanic rocks. For this division the term **hypabyssal**[1] is used. Plutonic and hypabyssal rocks are *intrusive*, while the volcanic rocks are *extrusive*.

The field relations of the plutonic masses suggest an intimate connection with the original magma-reservoirs, of which, indeed, in some cases, they may form a part. On the other hand, the shape assumed by a hypabyssal rock is of necessity regulated by the nature of the passage along which it is injected, or, in other words, its shape is that of the channel of escape; while volcanic rocks, having been erupted at the surface, appear in beds or streams.

The plutonic rocks, being essentially deep-seated, can only appear at the surface in places where there has been much denudation, the overlying strata having then been removed by erosive agencies (frost, rain, fluviatile and marine action, etc.); unless, as sometimes happens, they have been upraised by powerful earth movements. They are, therefore, exposed more frequently in the older than in the younger strata. For this reason, granites, syenites, diorites, gabbros and similar plutonic rocks were formerly considered by some geologists to have been intruded only in pre-Tertiary times. That this view is erroneous has been shown in places where the denuding agencies have been sufficiently powerful to expose plutonic rocks of comparatively recent age, as

[1] Brögger: Die Gesteine der Grorudit-Tinguait-Serie. *Vidensk. Skrifter I., Math.-natur. Klasse*, 1894, No. 4, p. 123.

in the Western Isles of Scotland, where granites and gabbros, etc., have been intruded into bedded basalts of Tertiary age.

The following terms are used in describing the chief forms in which the plutonic rocks occur :—

Stock or **boss.**—Any irregularly-shaped intrusion which cuts across the structure of the invaded formation. The contacts are often vertical or highly inclined, and there is no visible floor on which the erupted material rests. The word boss is sometimes used rather loosely, being used also for minor intrusions to which the above term should not strictly be applied.

Dome.—This term may be usefully employed to describe granite masses whose sides shelve away beneath the surrounding sediments, at first at a comparatively low angle, the exposed area being

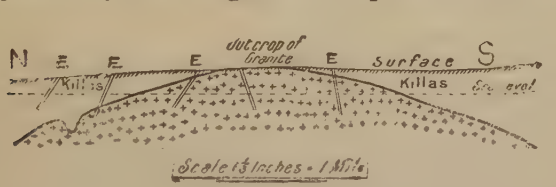

FIG. I.

Section through a granite dome intrusive in the Killas and penetrated by dykes of Elvan (E). (*After MacAlister.*)

usually circular or oval. This term implies no adhesion to a particular theory as to mode of origin, as is the case with bathylith and laccolith.

Bathylith.—This term was introduced to connote the characters of igneous masses, similar to stocks or

bosses, but of much larger size, and occurring typically in great mountain ranges (*mountain-core, central granite-core, massif*, etc.). Suess[1] defines a bathylith as a stock-shaped or shield-shaped mass which has originated by the melting, and assimilation by the intruding magma, of a portion of the invaded formation. When exposed by denudation, it is found either to maintain its diameter or to grow broader with increasing depth.

The assimilation theory thus applied by Suess to explain the origin of granite-bathyliths dates from a paper by Kjerulf[2] in 1879. Michel-Lévy[3] also has stated it very clearly in his studies of the French granites. It has not, however, found universal acceptance; Brögger,[4] for instance, maintains that the granite-massifs of the Christiania district are laccoliths rather than bathyliths in Suess' sense. It is beyond the scope of this book to discuss more fully so controversial a subject, interesting and important as it is. The references given to the literature will enable the student to plunge as deeply

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[1] *Sitzungsberichte der Wiener Akademie*, vol. civ. (1895), p. 52. "Eine stock oder schild-förmige Durchschmelzungsmasse, welche mit fortschreitender Abtragung entweder den Querschnitt behauptet oder breiter wird, bis in die 'ewige Teufe.'"

[2] Kjerulf: Udsigt over det sydlige Norges geologi. Christiania, 1879.

[3] Michel-Lévy: Contributions à l'etude du granite de Flamanville et des granites français en général. *Bull. des services de la carte géol. de la France.* No. 36, 1893.

[4] Brögger: Die Eruptionsfolge des triadischen Eruptivgesteine bei Predazzo in Südtyrol. *Vidensk. Skrifter*, 1895, No. 7, p. 116.

into the subject as he may desire. Brögger's and Michel-Lévy's works should especially be consulted.

While on this subject, it may be pointed out that it has been held that certain rocks of plutonic character may be produced by the fusion of deeply buried sediments even without the aid of magmatic intrusion. Thus Lawson [1] has described in the Rainy Lake district of Canada vast areas of rocks of plutonic habit which, according to him, have originated by the fusion of sedimentary rocks. This is supposedly brought about by the rise of the geo-isotherms, consequent on the deposition of great thicknesses of sediments in a sinking area.

We have now to consider the forms assumed by rocks that have been produced by the injection of the magma, fed from deeper-lying reservoirs, into channels or chambers produced by the parting of the invaded formation. It is evident that the injection must have taken place either across or along the planes of stratification. Dykes and volcanic necks are instances of the former mode of injection, sills and laccoliths of the latter.

Dykes.—A dyke is a wall-like mass of igneous rock, produced by the injection of molten material into a fissure. It has nearly or quite parallel walls, and its length is considerably greater than its width. It may vary in inclination from vertical to horizontal, but it is a *sine quâ non* that it cuts across the bedding when the invaded formation is stratified. Should there have been successive injections of similar

[1] *Report of the International Geological Congress*, London, 1888.

material in the same fissure, the finally resulting mass is termed a *multiple dyke*. Should the successive injections be of different magmas, the resulting mass is termed a *composite dyke*. The Tormore dykes of Arran are a good example of composite dykes.[1] Examples of both types have been described by Harker in Skye.[2] Dykes sometimes form marked features in the scenery of a district; for, being more capable of resisting the disintegrating action of the weather than the rocks they traverse, they remain standing,

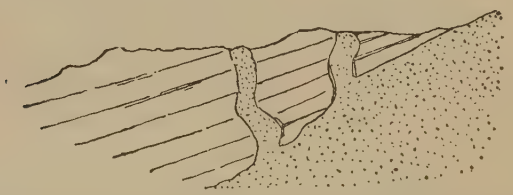

FIG. 2.

Section showing granite sending apophyses into a bedded rock.

(*After De la Beche.*)

like huge walls, when the softer rocks have been worn away. Occasionally, however, they weather more rapidly than the surrounding material, and then produce hollow troughs. Quartz-porphyries, lamprophyres, dolerites, etc., occur as dykes; *e.g.*, the quartz-porphyry dykes of Cornwall, the lamprophyre dykes of Yorkshire and Westmorland, the

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[1] Judd: *Quart. Journ. Geol. Soc.*, 1893, p. 564.

[2] Harker: The Tertiary Igneous Rocks of Skye. *Mem. Geol. Surv.*, 1904, pp. 201 and 206.

dolerite dykes of the North of England and the West of Scotland.

Veins.—Veins are produced by the injection of the magma into smaller and less regular fissures than those that give rise to dykes. When such veins represent the infilling of cracks in the partially consolidated rocks with a residual portion of the same magma, they are termed *contemporaneous veins.*

FIG. 3.

Plan showing granite veining slates. (*After De la Beche.*)

Apophyses or tongues.—These are dykes or veins that are in visible connection with the larger intrusive bodies which supplied their magma. Owing to the different physical conditions under which the rock composing an apophysis has consolidated, it usually possesses a micro-structure unlike that of the large intrusive body with which it is connected, although

the chemical composition of the two may be identical.

Necks.—Necks are the filled-up pipes or vents by which the erupted material made its escape. Usually they are plugs of consolidated igneous rock, surrounded by beds of volcanic ejectamenta. Sometimes, however, they consist entirely of fragmentary material produced by the violence of the explosions

FIG. 4.

Volcanic necks in New Mexico, U.S.A.

that precede or accompany an eruption. As examples, the necks developed in western New Mexico, and the Bass Rock and North Berwick Law, in Haddingtonshire, may be cited.

Laccoliths.—A laccolith is a dome-shaped intrusion; it may be conveniently regarded as a special case of sill, in which the intrusion of the magma has been accompanied by an up-arching of the overlying beds. As a rule the base remains flat: a laccolith

grows "by up-lifting its cover."[1] The ground-plan approximates to a circle, but may be an elongated oval with the long axis in the direction of the strike of the invaded strata. While in sills or sheets the lateral dimensions are very great as compared with the thickness, in laccoliths the thickness approximates

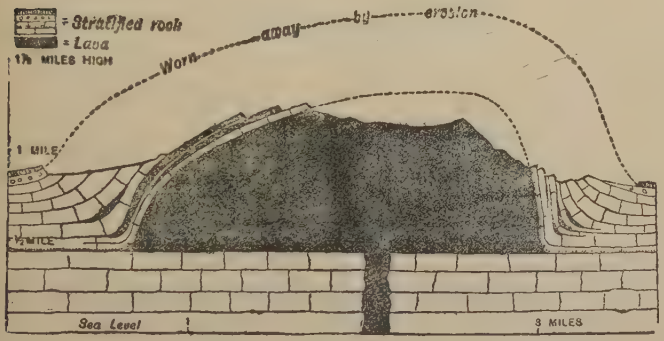

FIG. 5.
Laccolith forming Mount Hillers, Henry Mountains.

to the width. Laccoliths may be multiple (as in the case of the so-called *cedar-tree laccoliths*), or composite (as, for example, the gabbro-laccolith of the Cuillin Hills described by Harker[2]).

The laccolith theory of the origin of igneous rocks has met with very general acceptance, and many large plutonic intrusions are now considered to be laccoliths. Brögger even regards the largest granite

[1] Gilbert: The Geology of the Henry Mountains; *U.S. Geol. Survey*, Washington, 1877.

[2] The Tertiary Igneous Rocks of Skye. *Mem. Geol. Surv.*, 1904, p. 87.

intrusions (*e.g.*, those of the Christiania district) as laccoliths rather than bathyliths. (See p. 10.)

Laccoliths were first described by G. K. Gilbert in the Henry Mountains of Utah, where they are very typically developed and well exposed. Many of the

FIG. 6.

Section of a composite laccolith in bedded basalts of Allt an 't-Sithean and Cnoc an 't-Sithean, Sligachan, Skye. The basalt of the laccolith is shown black and the granophyre white. The bedded basalts are cross-hatched. (After Harker: The Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 209.)

intrusive rocks of North Wales have an outcrop which indicates a laccolithic origin; and the same is probably the case with some of the acid intrusives of the Central Highlands of Scotland. According to Harker,[1] some of the acid and basic intrusions of the Red Hills and the Cuillin Hills in Skye have the general habit of laccoliths; and in this connection attention must be drawn to the fact that, in the case of very large laccoliths, we have conditions of magma-consolidation closely similar to those of the deep-seated magmas; consequently, it is to be expected that rocks so formed should have plutonic characters. This, indeed, is found to be the case in

[1] The Tertiary Igneous Rocks of Skye. *Mem. Geol. Surv.*, 1904, p. 83.

the example quoted from Skye, where rocks of plutonic habit (granite and gabbro) are found to grade into rocks of true hypabyssal type (granophyres and dolerites).

Bysmalith or plug.—As defined by Iddings[1] a bysmalith is an injected body, having the shape of a cone or cylinder, which has either penetrated to the surface or terminates in a dome of strata like that over a laccolith. The "plutonic plug" of Russel[2] is a similar conception. Vertical displacement with faulting is the characteristic of this method of intrusion. Mount Holmes, in Yellowstone Park, is cited by Iddings as a type.

Intrusive Sheet or sill[3]—A flat bed of rock produced by the uniform intrusion of molten material

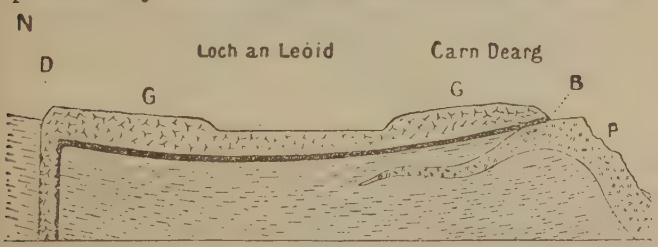

FIG. 7.

Section of a composite sill, Carn Dearg, near Suishnish, Skye. Scale 6 inches to a mile; G. Granophyre portion of sill; B. Basalt portion; D. Supposed dyke-feeder of sill (After Harker: Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 211.)

between the planes of stratification. When the intrusion is repeated between many planes of strati-

[1] *Journ. of Geol.*, vol. vi., 1898, p. 707.

[2] *Journ. of Geol.*, vol. iv., 1896, pp. 23-43.

[3] The word sill for a flat bed is derived from the Great Whin Sill of the North of England.

fication, it is known as *lit-par-lit* intrusion. Sills are liable to be mistaken for contemporaneous lava-flows;[1] from which, however, they may be distinguished by the following points of difference: (1) they break across the bedding, appearing here on one horizon, there on another; (2) they sometimes send off veins into the strata above them, as well as into those below them; (3) they alter the beds both above and below them; (4) they are rarely vesicular

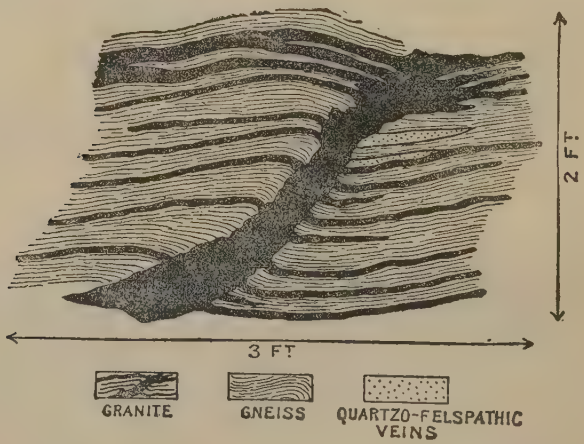

FIG. 8.

Lit-par-lit intrusion of granite in a foliated rock (gneiss). *Summary of Progress, Geol. Surv.*, 1907, p. 78.

or amygdaloidal; (5) they are not accompanied by tuffs. As in the case of dykes, sills may be multiple or composite. Examples of both have been described

[1] Mr. Harker points out that the sill-formed intrusions in the basic lavas of Skye have to a large extent not been discriminated from the flows. *Loc. cit.*, p. 29.

by Harker in Skye.[1] Dolerites frequently occur in intrusive sheets, and constitute one of the most striking features of many igneous areas, for example, Cornwall, the English Lake District, North Wales, Western Isles of Scotland, and Fife. The Whin Sill in the North of England is an intrusive sheet of basic rock, which, though never more than 150 feet thick, extends for a distance of 80 or 90 miles.

Lava-flows.—Lava is the molten rock poured out from a volcanic vent. The flow is *subaërial* or *submarine*, according as the eruption took place on land or on a sea-bottom. In subaërial flows the lava forms beds or streams of greater or less extent, according to the fluidity of the erupted material, the more basic magmas being the more fluid. Thus the Icelandic basalts were so liquid that they flowed in streams for a distance of 40 to 50 miles; while, on the other hand, the acid trachytic lavas of Auvergne in Central France were erupted in such a viscous condition as to form hummocky or dome-shaped masses of small lateral extent.

When the flows took place in an area of deposition, *e.g.*, on a sea-bottom, the lava-beds lay upon, and were covered by sedimentary rocks of practically the same age as themselves. In such cases they are said to be *contemporaneous* with the strata with which they are interbedded. Submarine eruptions began in pre-Cambrian times, so that contemporaneous igneous rocks occur in formations of various ages.

[1] Harker, *loc. cit.* A resumé of the literature of the subject is given on p. 199.

Bedded lavas constitute a notable feature in the physiography of certain parts of the British Isles. Much of the beautiful scenery of North Wales and of the Lake District owes its origin to the great development of volcanic lavas (rhyolites and andesites), erupted in the Ordovician period. The Cheviot andesites are Old Red Sandstone lavas. Plateaux of Carboniferous basalt cover large areas in the Midland Valley of Scotland; while bedded basalts of

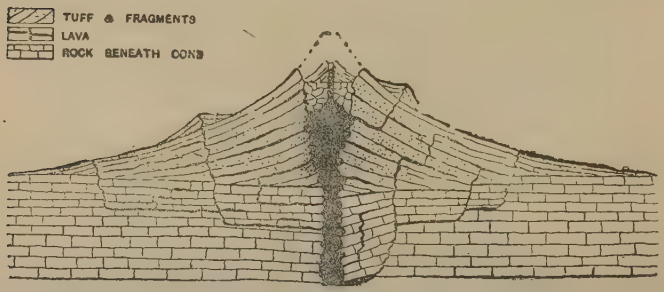

FIG. 9.

Ideal section of a volcano.

Tertiary age are extensively developed in the North of Ireland and in the Western Isles of Scotland. Basalt-plateaux of a similar character, but on a much grander scale, occur in some of the Western States of North America (Idaho, Oregon, and Washington); and in India an area of 200,000 square miles is covered by the basaltic flows known as the "Deccan traps." On account of the absence of pyroclastic accumulations in these basalt-plateaux, the lava is considered to have been fed through dyke-fissures; and

this form of intrusion, which is known as "*fissure-eruption*," has taken place even within historical times in Iceland.[1]

Volcanic Ash-beds, or tuffs.—When the eruption is accompanied by explosion, the molten rock is ejected in the form of bombs, cinders (*lapilli*), and fine ash, which are deposited in layers. The consolidation of this pyroclastic material produces volcanic breccias

FIG. 10.

A thin section of a volcanic tuff, showing its fragmental nature. (*After Cole and Jennings.*)

or tuffs, according to the degree of coarseness of the fragments. The fragmentary material ejected from volcanoes often becomes mixed with the ordinary sediment of the sea-bottom, producing ashy limestones and ashy shales.

[1] Thoroddsen : *Geog. Journ.*, vol. xiii. (1899), p. 500.

CHAPTER II.

EXTERNAL STRUCTURE.

WHILE in the aqueous rocks the most characteristic feature is the stratification of the deposits, the igneous rocks are essentially unstratified. In general they may be said to possess a *massive*, in contradistinction to the *bedded* character of the sedimentary rocks through which they are usually intruded. There are, however, some cases in which rocks of igneous origin are traversed by horizontal divisional planes, which resemble those of stratification. Thus the intermittent outpouring of lava from a volcanic vent produces a rock which has a true bedded character, each bed representing a distinct flow. Again the differential movement of an igneous mass in a plastic or semi-solid condition causes it to assume a laminated or "fluidal" structure on consolidation. Flow-structures of this kind in rocks of igneous origin have occasionally been mistaken for stratification.[1] Horizontal jointing in massive rocks may also simulate a thick-bedded character. Thus granite, when exposure to the corrosive action of the weather

[1] The parallel structures produced in igneous rocks by dynamic or pressure metamorphism might also be instanced as examples of "pseudo-stratification."

has brought out its divisional planes, often presents a rudely bedded appearance, which at a distance may be mistaken for stratification. (See Figs. 11 and 12.)

For the moment, we have to consider what are the external structures produced as a result of the consolidation of an igneous rock from a molten condition.

FIG. 11.
Mural jointing in granite.

The micro-structure or texture of igneous rocks will be treated subsequently.

Reference must first be made to the planes that are developed by shrinkage or contraction in passing from the liquid to the solid state. The divisional planes known as *joints* are found in all varieties of igneous rock; and the appearance of a rock laid bare in a quarry or other section, is to a large extent dependent on its mode of jointing. The joints may be disposed in an irregular manner, or the parallelism of one or more systems of divisional planes may impart a more or less definite structure to the rock. The "mural jointing" of granite, which was referred to above, is mainly caused by a system of roughly parallel planes. In the so-called *sheet-structure* the parallelism is still more pronounced. (See Fig. 12.) A *platy structure* is produced by the parallelism of plane joints not far removed from one another. This structure is found in dykes in

which the divisional planes are parallel to the bounding walls. In some rocks the surfaces of separation appear to form the concentric shells of a large spherical system of jointing. This character is well exemplified in the rock known as phonolite,

FIG. 12.

Pseudo-stratification in granite due to horizontal jointing or "sheet-structure." Crabtree and Havey Quarry in Sulivan, Maine. (*After T. N. Dale.*)

which has a tendency to split into slightly curved plates.[1] A micro-structure of a similar nature frequently developed in vitreous rocks is known

[1] The spheroidal weathering of some greenstones is due to a joint-system of this nature, the existence of which is only demonstrated by the facility it offers to the progress of decomposition.

as the *perlitic structure*. (See Fig. 13.) In all such cases the concentric-laminated structure is produced by concentric fissuring due to contraction on cooling.

When a rock is traversed by two or more systems of shrinkage-joints, a *columnar structure* results. Many igneous rocks present this mode of jointing, but the structure reaches its most perfect develop-

FIG. 13.

Perlite of Tokay, Hungary, under the microscope, illustrating Perlitic and Flow-structures. (*After Fouqué and Lévy.*)

ment in basic rocks: the columns, which are often very long and regular, are bounded by three, four, five, or six planes, producing triangular, quadrangular, pentagonal, and hexagonal prisms. Where the rock-texture is homogeneous the six-sided prisms are most prevalent, for in this case the centres of

contraction are equidistant, and the angles of the prisms fit together without any intervening space. The long axes of the columns are perpendicular to the surface at which the greatest cooling took place. In accordance with this law the columns are

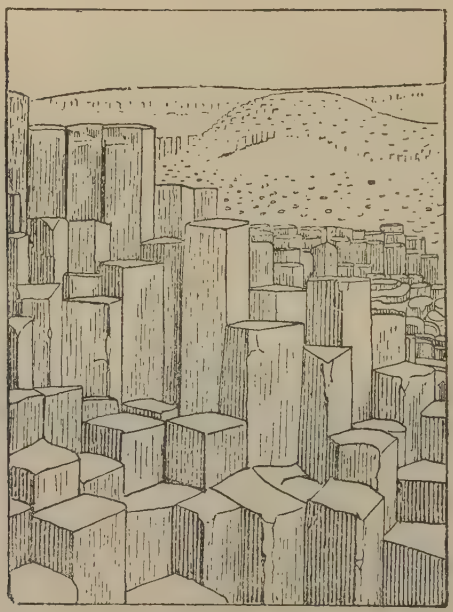

FIG. 14.

Columnar basalt, Giant's Causeway, Ireland.

vertical in horizontal sills and flows; while in dykes they are horizontal if the walls are vertical. Fine examples of columnar jointing are found in the basic rocks of the Western Isles of Scotland as at

Staffa and in Skye, also at Elie and St. Andrews in Fifeshire. Occasionally the columns are subdivided into segments by a subsidiary cross-jointing, and usually such segmentation is accompanied by a spheroidal tendency, producing *ball-and-socket* joints. Good examples are seen in the Giant's Causeway in the North of Ireland, and in the Cheese Grotto at Bad Bertrich in the Eifel.

Lavas are distinguished by marked *flow-structures* (ropy and stringy surfaces, internal streakiness, etc.), due to the rolling-over and pulling-out of the semi-solid mass. They are also characterised by a cellular or scoriaceous character, produced by the elimination of water-vapour from the magma on its eruption. Innumerable steam bubbles are developed in the viscous liquid, and their retention in the solidifying lava produces a *vesicular structure*, which reaches its maximum development in the substance known as pumice. The vesicles are usually drawn out in the direction of flow, and in extreme cases become extended to long-branching, coral-like tubes as in the "pipe-amygdaloid" of the Volcanic Beds of the Drakensberg and Malutiberg in South Africa, and, more rarely, in the Tertiary basalts of the Western Isles of Scotland.

When filled with decomposition-products (calcite, zeolites, chalcedony, etc.), the almond-shaped vesicular cavities are known as *amygdales*, and the structure as *amygdaloidal*.

Vesicular structure is not found in the deep-seated rocks, but hypabyssal rocks are occasionally

[1] See A. Geikie: Ancient Volcanoes of Great Britain, 1897, p. 17.

amygdaloidal.[1] A structure genetically allied to the vesicular is found in some granite rocks that have consolidated under a comparatively shallow cover. In such rocks are small cavities of irregular shape, into which project well-shaped crystals. This means that the minerals, separating from the magma in the neighbourhood of a vapour cavity, attained a more perfect development than those constituting the bulk of the rock. This structure is known as the *drusy* or *miarolitic*, and is characteristic of the granites of the British Tertiary area (Mourne Mountains, Arran, Skye, etc.).

Reference may be conveniently made here to the dark-coloured patches (the *heathen* of the quarryman) which are of frequent occurrence in some granites. Some of these are generally, and probably rightly, regarded as having been produced, during an early period of the solidification of the magma, by the segregation of its more basic constituents[2]; but in many cases, especially when they occur in the marginal portion of the intrusion, they are undoubtedly included fragments of foreign rocks that have been caught up by the magma during its intrusion. For such inclusions the name **xenolith** has been proposed.[3] In some cases xenoliths occur in such abundance as to impart to the granite,

[1] A. Geikie: *Trans. Roy. Soc. Edin.*, vol. xxxv., p. 38.

[2] J. A. Philips: *Quart. Journ. Geol. Soc.*, xxxvi. (1880), pp. 1-2, and xxxviii. (1882), pp. 216-217.

[3] Sollas: *Trans. Roy. Irish Acad.*, vol. xxx. (1894), p. 502. For inclusions of single crystals of a foreign mineral the same author uses the term **xenocryst**.

by their parallel arrangement, partial fusion and "streaking out," a local banded or gneissose structure.[1] The researches of Harker[2] in Skye show that the character of an igneous rock may be materially modified by the incorporation of xenoliths of another. In such cases the intrusion of the later rock probably took place before the consolidation of the earlier was completed.

Certain structures which might perhaps be regarded as external, and as such receive treatment here (*e.g.*, the banded, and the spheroidal or orbicular structures), are for convenience referred to in the next section, which deals with the micro-structures of the igneous rocks. (See page 48.)

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[1] Lacroix: Le granite des Pyrénées, 2nd Mem., *Bull. des services de la carte géol. de la France*, No. 71, 1900, pp. 21 and 25.

[2] The Tertiary Igneous Rocks of Skye. *Mem. Geol. Surv.*, 1904.

CHAPTER III.

TEXTURE OR MICRO-STRUCTURE.

THE examination of a thin section of an igneous rock under the microscope shows that it is composed either entirely of crystals, or of crystals embedded in a paste or groundmass of a more or less imperfectly individualised glassy substance, or lastly of glass alone. Rocks of the first type are termed **holo-crystalline**; those of the second, **hypo-crystalline**; and those of the third, **vitreous**. The internal structure or texture of a rock depends mainly on the relation existing between the crystals themselves, or between the crystals and the groundmass, and in the latter case, to some extent, on the character of the groundmass itself; it will vary according to the conditions under which solidification took place, since the crystals were formed by molecular aggregation in a rock-magma during the process of cooling. Rocks that from the nature of their environment were caused to cool rapidly, are composed entirely or in great measure of glass; but when the conditions were such as to allow of a gradual loss of heat, the molecules had time and opportunity to group themselves into definite mineral

species, and a crystalline or hypo-crystalline texture is the result.

Sometimes it is the whole body of the rock that is vitreous; sometimes there is only a narrow "selvage" of glass, representing the rapidly chilled portion of the magma that came into immediate contact with the cooling surface. There is, naturally, every grada-

FIG. 15.
Globulites.

FIG. 16.
Margarites.

tion between rocks that consist wholly of glass and those that are completely crystalline. The glassy base, even of vitreous rocks, is seldom completely devoid of crystalline material. Examined with the microscope, it is often found to contain numerous minute, spherical, rod-shaped, and hair-like bodies,

FIG. 17.
Trichites.

FIG. 18.
Belonites.

which represent the first products of crystallization These bodies are in general termed **crystallites**.

They are not crystals, for they possess no distinct crystallographic form, nor do they react on polarized light. The different forms have received specific names: thus, the drop-like bodies are termed *globulites;* the rod-shaped ones, *belonites;* and the coiled and twisted hairs, *trichites.* (See Figs. 15-18.)

Besides crystallites there are small needle- and rod-shaped bodies which are known as **microlites.** They are distinguished from crystallites by the fact that they react on polarised light (becoming alternately light and dark when rotated between crossed nicols), and can generally be referred to

FIG. 19.

Skeleton-crystals of olivine. (*After Rosenbusch.*)

some mineral species—felspar, augite, olivine, magnetite, etc. By combination of the simple microlitic forms, curiously forked and gridiron-like aggregates (*skeleton-crystals*) are produced. (See Figs. 19 and 20.) The linear arrangement of these various bodies, and the way in which they sweep round the larger crystals, serve to indicate the once fluid nature of the vitreous rocks in which they are found (*fluxion-* or *flow-structure*).

An incipient form of crystallization, often met with in vitreous rocks, consists in the production of small

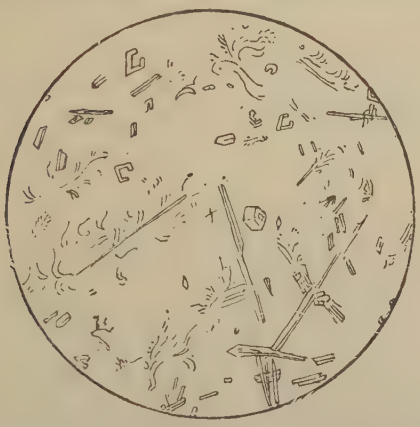

FIG. 20.

Pitchstone of Arran, under the microscope, showing microlites and keleton-crystals of hornblende in a glassy base. (*After Teall.*)

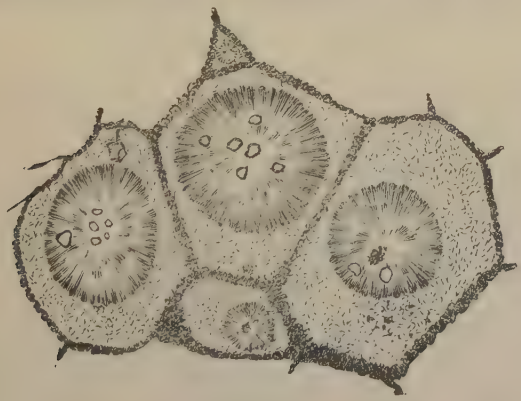

FIG. 21.

Spherulitic structure in a felsite of Arran.
(*After Bonney.*)

spherical bodies, known as **spherulites.** These bodies, usually of the size of a pea or smaller, present, when viewed under the microscope, a divergent fibrous structure, and are characterized between crossed nicols by a black cross, the arms of which are parallel to the short diagonals of the two nicols. These fibro-radial crystalline aggregates were

FIG. 22.

Spherulitic structure, between crossed nicols. (*After Fouqué and Lévy.*)

produced during the final period of solidification, or subsequently thereto; for streams of microlites sometimes pass through them, showing that the formation of crystals and the arrangement of them in lines of flow preceded the growth of the spherulites.

The separation of minerals from a silicate-magma which is slowly cooling is determined by the readiness with which the different minerals will form supersaturated solutions, by mass-action, by the chemical affinity of the different bases for one another and for silica, and by the pressure to which the magma is subject. As a preliminary to the discussion of the micro-structure or texture of a crystalline or hypo-crystalline rock, we must consider the conditions under which minerals are produced in a molten magma that is undergoing solidification.

Lagorio[1] has shown that silicate-magmas behave as solutions, and that therefore the laws established with reference to the separation of salts from saturated and supersaturated solutions, can be applied to explain the formation of minerals in an igneous magma, which may be regarded as a mutual solution of the silicates that build up the complex minerals of igneous rocks. *Crystals tend to form in a magma when it becomes sufficiently supersaturated with any definite compound.* The gradual diminution of temperature causes successive supersaturation with different compounds, which would therefore crystallize in the order of their solubility, but for the modification produced by the relative proportion and chemical affinity of the different bases present as silicates. The order in which the silicates of the metallic oxides tend to saturate molten silicate solutions, is given by Lagorio as follows: first, the oxides of the

[1] *Min. u. Petr. Mitth.*, vol. viii. (1887), pp. 421-529.

heavier metals (the sesquioxide of iron more easily than the protoxide); then follow in order magnesia, lime, soda, alumina, and potash.

The influence of mass in determining the formation of minerals is illustrated by the poorness of the acid rocks in iron-ores, the excess of silica in such rocks having united with the iron to form iron-silicate. Again, when iron-ore is developed in acid rocks, it is as magnetite; whereas in basic rocks, ilmenite predominates: the excess of silica in the acid rocks draws the titanic acid to combine with it to form sphene, while in the basic rocks the latter is left free to combine with the iron-oxides.

The influence of relative proportion and chemical affinity of the bases on the separation of minerals in a slowly cooling magma, is illustrated by a case quoted by Harker[1] from the Isle of Rum. In a series of rocks composed essentially of olivine and anorthite, the olivine is found to have crystallized out first when the rock is rich in that mineral, while in varieties rich in the felspar, the reverse holds good. Only when the two minerals occur in a certain fixed proportion, one to the other, have they crystallized simultaneously. Vogt's researches on slags[2] show that, *when a pair of minerals are in mutual solution, there is a certain definite ratio of the one to the other in which they will crystallize out in intimate admixture.* Whichever mineral is in excess of this

[1] *Science Progress*, 1907, p. 245, and Geology of the Small Isles, *Mem. Geol. Surv.*, 1908, p. 85.

[2] Die Silikatschmelzlösungen: *Vidensk. Skrifter, I. Math.-natur. Klasse*, 1903 and 1904, Christiania.

(the *eutectic* [1]) proportion, will separate out first. Only when the residual magma contains the two minerals in the eutectic proportion, will they crystallize simultaneously in intimate intergrowth.

The eutectic ratios for certain pairs of minerals crystallizing from slags, have been established. For augite and olivine it is as 68 : 32 ; for plagioclase and olivine, 70 : 30. Teall [2] suggested in 1888 that the interstitial micro-pegmatite of acid rocks is an eutectic mixture of quartz and felspar, and represents the final mother-liquor from which the other minerals have crystallized out. Subsequently Vogt showed that the eutectic ratio of quartz and felspar corresponded approximately to 26 parts of the former to 74 of the latter.

The order of crystallization of a pair of minerals which do not form mixed crystals can be exemplified by means of a temperature-concentration diagram, in which the concentration of the relative proportions of the two components is shown in percentages by abscissæ, and the temperature by ordinates. Take for instance the case of the anorthite-olivine magma already quoted.

In the diagram (fig. 23) the point A on the concentration line represents 100 per cent. of anorthite, and the point O, 100 per cent. of olivine. Points lying between A and O represent all possible mixtures of these two minerals. Further, A′ on the temperature line represents the freezing point of pure anorthite, and O′ that of pure olivine. Starting with pure

[1] F. Guthrie : *Phil. Mag.*, 1875, p. 20.

[2] *British Petrography*, London, 1888, p. 395-419.

anorthite, the addition of an increasing proportion of olivine lowers the freezing point, as shown by the curve A′E′, and similarly the addition of anorthite to olivine produces the freezing point curve O′E′. These two curves intersect at E′. The point E at which the vertical from E′ cuts the concentration line, gives the composition of the eutectic of anorthite and olivine.

Given a magma represented in composition and temperature by the point P, and subject to a falling temperature, no consolidation will take place while

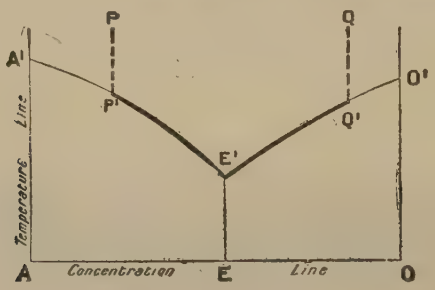

FIG. 23.

the temperature falls from P to P′. But at P′ the constituent (here anorthite) which is in excess of the eutectic proportion begins to separate in the pure form, and the system moves (by fall of temperature and change of composition of the residual liquid) along the curve P′E′. On reaching the point E′, the whole liquid consolidates as the eutectic, without further change in composition. If, on the other hand, we start at a point Q, representing a liquid in which olivine is in excess, a similar result is obtained, but pure olivine first separates.

If in addition to the two minerals a third be present, say pyroxene in the case quoted, Nernst's law of the reduction of solubility between substances having a common *ion*,[1] appears to govern the order of crystallization. Thus olivine and pyroxene have the ion (Mg Fe) in common, consequently the solubility of the olivine is much reduced, and it invariably crystallizes before the felspar, even when not present in very large amount.[2]

The effect of pressure on the separation of salts from solutions has been investigated by Sorby.[3] He has shown that the solubility of salts which increase in volume as they pass into solution, is lowered by pressure. The rock-forming silicates behave in a like manner. Consequently, a magma which at a given temperature and pressure is on the point of crystallizing will, if the pressure be relieved, remain liquid, until, by the fall of temperature, the proper point of saturation has been reached. This affords an explanation of the corrosion and resorption of crystals that have been formed in a magma prior to eruption. The relief of pressure consequent upon eruption lowers the fusing point of the mineral, and a portion of it passes into solution, separating out again in many cases during a later phase of consolidation. Since a decrease of temperature induces crystallization, while a decrease of pressure retards it, it is conceivable that, in a magma subject to changing

[1] Nernst: Theoret. Chem., 3rd edit. (1904), p. 492.

[2] Harker: Geology of the Small Isles, *Mem. Geol. Surv.*, 1908, p. 86.

[3] *Proc. Roy. Soc.*, vol. xii. (1863), p. 538.

temperature and pressure, the development and retardation of crystallization might be several times repeated, thus affording an explanation of the *zones of resorption* which are often observable in the larger crystals of hypabyssal and volcanic rocks.

In the hypabyssal and in the volcanic rocks there are often two distinct phases of consolidation. The first phase consists in the formation of **porphyritic**[1] crystals, or **phenocrysts**,[2] whose growth is promoted by molecular currents in a magma of extreme liquidity. This has been termed by Rosenbusch the *intratelluric phase of crystallization*, signifying thereby that the crystals were produced before the eruption of the rock, while it was still in its original magma-basin. The second phase consists in the comparatively rapid solidification of the magma, which becomes the groundmass in which the phenocrysts are embedded. The groundmass usually contains a second crop of the minerals belonging to the first phase, together with those minerals that only appear in the groundmass. If the crystallization was complete, the groundmass is *holocrystalline*. More usually, however, a residual mother-liquor remains after the separation of the crystals, and consolidates as glass. This is known as the *glassy base*.

According to Crosby,[3] the coarse granular texture of some deep-seated rocks implies a uniformly

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[1] So named because such crystals constitute the typical character of the rocks known to the ancients as *porphyry*.

[2] Iddings (*Bull. Phil. Soc. Wash.*, vol. xi., 1888-1891, p. 73) from *φαίνω*, I show, and *κρύσταλλος*, crystal.

[3] *Amer. Geologist*, vol. xxv. (1900), p. 299.

slow rate of cooling which enabled the wide-spaced immobile crystals of the first phase to continue to grow until the magma was exhausted without fresh centres of crystallization being set up. Such a granitoid rock may be regarded as consisting wholly of overgrown phenocrysts. In magmas which by their environment are subject to a more rapid rate of cooling, a condition of viscosity may be quickly attained which is too great for free molecular diffusion, and crystallization is started simultaneously at many narrow-spaced centres. The result is a finely crystalline granular texture, in which the rock may be regarded as consisting entirely of groundmass. In porphyritic rocks two phases of consolidation are presented. Such rocks are formed from magmas which at first, under the influence of slow cooling, started the formation of phenocrysts at widely-spaced centres of crystallization, with free molecular diffusion. A sudden change to a condition of increased viscosity checked the supply of fresh material to the growing phenocrysts, and induced the setting up of many new centres, with consequent rapid consolidation to a groundmass. This abrupt change from centralized to diffused crystallization is consequent upon an increased rate of cooling, which, in the case of the volcanic rocks, is brought about by their effusion, and in the case of the hypabyssal rocks, by their transference from deep-seated to superficial portions of the earth's crust. The relief of pressure at the moment of extrusion or injection may, as already pointed out, cause at first a partial resorption of the

phenocrysts; but the increased rate of cooling, aided by the escape of occluded water, speedily induces a magmatic condition analogous to that of an over-cooled or super-saturated solution, and solidification of the magma-residuum speedily takes place.

The occasional occurrence of the porphyritic structure in the heart of a bathylith, where the abrupt change in the rate of the cooling postulated by Crosby's theory cannot conceivably take place, may best be explained in the manner suggested by Professor Miers.[1] He has shown that experimental evidence confirms the suggestion of Ostwald that there are two states of super-saturated solution, namely, a labile and a metastable.

A super-saturated solution is *labile*, when crystallization can take place in it spontaneously; and at a somewhat higher temperature it is *metastable*, when crystallization can only be induced in it by the introduction of a solid fragment of the dissolved substance. Applying this to a silicate magma which is at a sufficiently high temperature to be in the metastable state, is cooling slowly enough to remain in that state for a considerable time, and is sufficiently viscous to prevent the growing crystals from sinking, we have the conditions suitable for the growth of porphyritic crystals. These must have originated as spontaneous nuclei if the magma had temporarily entered the

[1] British Association Rep., 1905. Presidential Address to Section C.

labile state; or they may have been started by inoculation or by marginal cooling, which may reduce it locally to the labile state, though the magma as a whole may have remained metastable. If, when the porphyritic crystals have attained a certain size, the magma, by a somewhat sudden increase in the rate of cooling, enters into the labile condition, spontaneous crystallization will be started at many centres, and a groundmass will be produced in which there will be a second generation of one of the constituents of the rock.

The special case of the production of the porphyritic structure in a quartz-felspar magma in which the magma-residuum solidifies as micropegmatite, has been explained thus.[1] The magma having reached, by cooling, the labile state of saturation, the crystallization of quartz starts spontaneously at a number of centres. But by its separation, super-saturation is relieved, the magma becomes metastable, and the crystals already started continue to grow as the temperature falls. Since there are no felspar crystals to start the separation of that mineral, the formation of quartz will continue beyond the limit required by the eutectic ratio. The continued subtraction of quartz then leaves the felspar in excess, so that when the cooling magma reaches the labile stage for that mineral, felspar alone will crystallize. Finally, when the separation of the excess of felspar brings the magma again to the eutectic point, the presence of crystals of both

[1] Harker, *loc. cit.*, p. 251.

minerals causes their simultaneous crystallization in the form of micro-pegmatite.

Having thus briefly discussed the conditions under which rock magmas may be supposed to solidify, we must turn our attention to rock textures, which are genetically dependent on the conditions of solidification. As already pointed out, the micro-structure of rocks is determined both by the shapes of the constituent crystals and by their arrangement with respect to one another and to the glassy base, if such be present. First with regard to the shape of the crystals: those forms in which the crystal contours are more or less perfectly developed are termed **idiomorphic**; while those in which the formation of the crystal contours has been prevented are termed **allotriomorphic**[1] (see page 73).

In respect to the size of the grain, the structure of a holocrystalline rock may be *coarsely crystalline*, *finely crystalline*, or *micro-crystalline*. These terms explain themselves. A rock which is apparently homogeneous may be found, when examined in thin sections under the microscope, to consist of an aggregate of minute granules, some of which act upon polarized light but are too small for even microscopic determination. This is what is meant by the term *cryptocrystalline*.

The micro-structures or textures dependent on the arrangement or relative position of crystals, may be

[1] These terms were introduced by Rosenbusch. Some authors (*e.g.*, Zirkel and Iddings) use Rohrbach's terms *automorphic* and *xenomorphic*, which express the same idea.

considered under the heads of juxtaposition, interposition, porphyritic structure, orbicular structure and banded structure.[1]

Juxtaposition.

a. **Allotriomorphic granular** is the texture in which the crystals are of uniform size (equidimensional) and without crystal-contours. It is usually termed

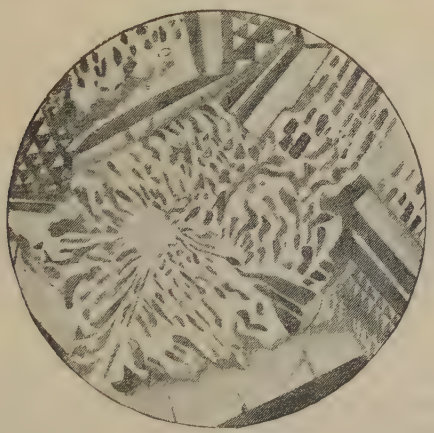

FIG. 24.
Granophyric Structure.

the *granitic structure*, and is presented mainly by the plutonic rocks.

[1] This classification is to some extent based on one given in the Quantitative Classification of Igneous Rocks by W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington ; Chicago, 1903. It is proposed by these authors to connote "the arrangement of the crystalline and non-crystalline parts of a rock" by the term *fabric* as opposed to *texture*.

b. **Hypidiomorphic granular**—similar to the preceding, but with a part of the crystals showing crystal contours.

c. **Pan-idiomorphic granular**—a texture in which all the constituents are bounded by crystal contours. There is often a dominant tabular or prismatic habit.

Interposition.

a. The **graphic** or **micrographic** structure is that in which two minerals mutually enclose one another by interpenetration. The most commonly occurring type is the *granophyric* structure, in which the two minerals in intimate intergrowth, but retaining their parallel orientation, are quartz and felspar. The intermixed minerals are, in this case, known as *micropegmatite*.[1]

There is a tendency in granophyric structure towards a divergent or radiate arrangement around a common centre or nucleus, which is usually occupied by a crystal of felspar (see Fig. 24) showing optical continuity with the felspar fibres of the framework. The radial character becomes more pronounced as the crystal needles or fibres became more slender. Such radially fibrous aggregates were named *pseudo-spherulites* by Rosenbusch; but every transition appears to exist between pseudo-spherulites of micropegmatite and the so-called microfelsite spherulites, in which the component mineral fibres are no longer distinguishable. Teall[2] first called attention to this,

[1] Another name used for such intergrowths of threads of felspar and quartz is *myrmekite*.

[2] *British Petrography*, London, 1888, p. 402.

and expressed the opinion that the latter represented a special modification of the former, and that both owed their origin to a simultaneous crystallization of the residual magma as quartz and felspar in the eutectic proportions. (See page 37.)

b. The **pœcilitic** or **poikilitic** structure[1] is that in which optically-continuous crystals of one mineral play

FIG. 25.
Ophitic Structure.

the rôle of matrix for crystals or grains of another which do not show parallel orientation, for example, olivine grains in pyroxene or hornblende. "Lustre mottling" is a consequence of the pœcilitic structure. A special type is the *ophitic* structure, presented by most dolerites. In this the felspar appears in

[1] Term introduced by G. H. Williams, *Journ. of Geol.*, vol. i. (1873), p. 176.

well-defined lath-shaped or tabular crystals, penetrating and enveloped by a groundmass of augite or hornblende.

Porphyritic, Orbicular, and Banded Structures.

The **porphyritic** structure is characterized by the presence of phenocrysts of one or more minerals in a groundmass of different material, which may be either crystalline, hypocrystalline or vitreous. Its origin has been discussed on page 40. The special type known as *glomero-porphyritic* [1] structure, is produced by the packing together of the porphyritic constituents, as in the Tynemouth dyke and the Peppercraig trachyte.

The **orbicular** structure is a form of crystal aggregation in which incipient forms are arranged radially as *spherulites* (see page 34), or in which definite minerals are grouped radially or concentrically round a common centre to form *spheroids*. The spherulitic structure occurs in glassy rocks; the spheroidal structure, in holocrystalline rocks (*e.g.*, spheroidal granite, orbicular diorite, etc.).

The **banded** structure is produced (1) by the linear arrangement of crystallites and microlites, or of crystals; (2) by the parallel arrangement of layers or streaks (*Schlieren*) [2] of rock showing different degrees of crystallization, or different proportions of

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[1] A term introduced by Judd, *Quart. Journ. Geol. Soc.*, vol. xlii. (1886), p. 71.

[2] A German term introduced by E. Reyer. See Doelter's Petrogenesis, p. 86.

the component minerals.[1] A typical example of the first type is quoted by A. Geikie and Teall:[2] in a sill of troctolite at Allival, in the Isle of Rum, the parallelism of the felspars is so pronounced as to impart to the rock a lamination which might easily be mistaken for the fissility of a schist. In the same paper the authors give an example of the second type: the gabbro of Druim an Eidhne, in the Cuillin Hills of Skye, which possesses a marked banding, due partly to differences of texture, and partly to variations in the proportion of the constituent minerals. This structure appears to have resulted from a differentiation of the parent magma into distinct but allied magmas, before eruption, so that the streaky character was impressed on the rock before crystallization commenced. This is shown by the fact that there is no parallelism of the constituent crystals. Harker,[3] however, points out that the heterogeneity which is necessary for the production of banded structure by fluxion, may also result from an admixture of magmas not derived from a common source.

The characteristic banded structure of rhyolites,

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[1] It is worthy of note that these structures are the result of flow before or during consolidation (*pseudo-gneissic* or *primary gneissic* structure of some authors), and must be distinguished from the banded structure produced by dynamic metamorphism, which is the result of molecular re-arrangement and flow after consolidation (*true gneissic* structure).

[2] On the banded structure of some Tertiary gabbros in the Isle of Skye. *Quart. Journ. Geol. Soc.*, vol. l. (1894), p. 649.

[3] *Quart. Journ. Geol. Soc.*, vol. lix., 1903, p. 215.

in which there is an alternation of glassy and crystalline layers or zones, in which spherulites are developed, is explained by Iddings [1] as depending on the variable amount of water vapour contained in different layers of the flowing magma.

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[1] *Journ. Amer. Geol. Soc.*, vol. xxxiii. (1887), p. 45. See also *Bull. Phil. Soc. Wash.*, vol. xi., p. 446.

CHAPTER IV.

COMPOSITION.

In discussing this part of the subject we have to distinguish between the *chemical* and the *mineralogical* composition of rocks. Although the latter is to some extent dependent on the former, rock-magmas possessing similar chemical compositions may develop different mineral products, when crystallized under other physical conditions. Differences in chemical composition, however, produce important mineralogical variations; and the chemical factor plays an important rôle in the classification of the igneous rocks.

Chemical Composition.

Rock-magmas are, without exception, silicate-magmas; that is, they consist of silica, together with the bases iron, alumina, lime, magnesia, potash and soda. If the silica is in excess of the bases, the solidified rock contains free silica or quartz, and such rocks are said to be **acid**. If, on the other hand, the silica percentage is low, the rock is said to be **basic**. In the acid rocks the percentage of silica may rise to 80; in the basic rocks it sinks to below 50, and in some ultra-basic

rocks even lower, reaching a minimum somewhere between 30 and 40. The proportion of silica greatly influences the crystallization of a magma. Acid magmas crystallize with more difficulty than the basic ones: consequently rhyolitic glasses (obsidian, pitchstone, etc.), are common, but basaltic glasses (tachylyte) are rare; again, at depths at which acid magmas solidify as fine-grained or porphyritic rocks, basic magmas, other conditions being the same, crystallize as medium-grained or even coarse-grained rocks.

Among the bases, alumina occupies an important place, being present in a great number of rock-forming silicates. While the greater proportion of this base is combined with alkalies to form the felspars (or felspathoids), a portion enters into the composition of the ferro-magnesian silicates (mica, hornblende, augite, etc.). The uncombined oxide occurs, somewhat rarely, as corundum. The percentage of alumina in rocks ranges from nothing, in the non-felspathic peridotites, up to about 20, in certain syenites.

The oxides of iron and magnesium also exert considerable influence in determining the character of a rock. The percentage of these bases is low in the acid, but rises considerably in the basic rocks. The lower oxide of iron (FeO) and magnesia are combined in an important series of silicates—the so-called ferro-magnesian minerals: olivine and the pyroxenes and amphiboles, or biotite, with the addition of potassium in the last-named. The same bases with the addition of lime form the lime-magnesian silicates

(the monoclinic pyroxenes and amphiboles). The oxides of iron are also abundantly present in the more basic rocks as free iron-ore (magnetite and ilmenite). Lime is an important factor: it takes an important part in the composition of the basic plagioclase felspars, but decreases as the felspars become richer in alkalies. It is also abundant in monoclinic pyroxene, less so in hornblende, and almost entirely absent from the rhombic pyroxenes and biotite. But of all the bases it is perhaps the alkalies, potash and soda, that are of greatest importance in determining the constitution of rocks. Thus together with alumina, and in some cases with lime, they form in combination with silica the felspars and felspathoids. According to the predominance of the particular base, we have: potassium silicates (orthoclase and leucite); sodium silicates (albite and nepheline); silicates of sodium and calcium (the basic plagioclase series); calcium silicate (anorthite). In rocks having an abnormally high percentage of alkalies, soda-amphiboles and soda-pyroxenes occur (*e.g.*, riebeckite, arfvedsonite, cossyrite, ægirine). Potash also enters into the composition of biotite.

Among compounds that occur in smaller proportions, although widely distributed, are phosphoric and titanic acids. The phosphate of lime (apatite) is present in most basic and in many intermediate and acid rocks; some apatite-bearing rocks even contain as much as two to three per cent. of phosphoric acid. Titanic acid is rarely completely absent, and may rise to five or six per cent., as in

certain basalts of Pantelleria.[1] Titaniferous iron-ore (ilmenite) is a frequent constituent of basic rocks; sphene (titano-silicate of lime) occurs in acid rocks, and perovskite (titanate of lime) in basic rocks. Small quantities of titanic acid appear also to be present in certain varieties of augite and mica.[2] Boron, fluorine and chlorine occur in small quantities in some igneous rocks. The last-named is chiefly present as a constituent of members of the nepheline-leucite group, while boron and fluorine are found in the minerals tourmaline, mica, topaz, fluorspar, and axinite, especially in rocks that have been subject to pneumatolytic modification.[3] Sulphur occurs, mainly as a constituent of pyrites, granules of which are dispersed through some igneous rocks. Carbon also occurs, chiefly in the form of graphite.

Among the metals, barium, strontium, lithium, chromium, vanadium, manganese, molybdenum, tungsten, nickel, and members of the platinum group are frequently present in minute proportions, especially in basic rocks. A series of Italian gabbros was found by Vogt to contain traces of chromic acid, ranging from 0·18 to 0·30 per cent.; and Dr. Pollard has found both chromium and vanadium in some of the

[1] Washington: *Quart. Journ. Geol. Soc.*, vol. lxiii. (1907), p. 74.

[2] The brown mica of Miask has been shown by Schäpfer to contain 4·73 per cent. of titanic acid; and Washington (*loc. cit.*) states that a colourless augite of Central Italy carries 2·85 per cent.

[3] Boron, fluorine and chlorine play an important rôle as so-called *mineralisers* in the crystallization of certain rock-magmas.

Skye rocks.[1] The researches of Sandberger have shown that the metals gold, silver, copper, mercury, and tin are also present in minute traces in igneous rocks; while native iron, in alloy with nickel and cobalt, has been found distributed in small particles through certain basalts.

The mean of a great number of analyses[2] of igneous rocks shows that the elements oxygen, silicon, aluminium, iron, calcium, magnesium, sodium, and potassium make up 99 per cent. of their chemical composition, and of these, oxygen alone makes up 47 per cent.

Mineralogical Composition.

With regard to the mineralogical composition of igneous rocks, the acid group is characterized by the presence of free silica or quartz in greater or less abundance, together with a dominant alkali-felspar. The intermediate group comprises rocks with little or no quartz, in which both alkali-felspars and members of the lime-soda series, as well as the felspathoid minerals (nepheline, leucite, etc.), play an important part. In the basic rocks quartz is absent, and the alkali-felspars generally so. Olivine, on the other hand, is frequently present. The pyroxenites and hornblendites constitute a type of basic rock in which both felspar and olivine are absent. Lastly, the most basic rocks consist for the greater part of olivine, together with

[1] The Tertiary Igneous Rocks of Skye. *Mem. Geol. Surv.*, 1904, p. 249.

[2] Clarke: Analyses of Rocks, *U.S. Geol. Surv., Bull.* 168 (1900), p. 15

smaller quantities of other ferro-magnesian minerals and iron-ores; when felspar is present it is the basic lime-felspar—anorthite. With regard to hornblende and augite, the former has a predilection for the more acid rocks, while the latter favours the basic rocks.

The rocks belonging to the acid group are in general of a light colour, owing to the predominance of siliceous and alumino-alkaline minerals.[1] As the basic character increases the colour becomes darker, owing to the greater abundance of ferro-magnesian minerals and iron-ores.[2] The specific gravity also increases with the basicity, being about 2·6 in acid rocks, and reaching as much as 3·6 in ultrabasic varieties.

The following estimate of the mean mineralogical composition of igneous rocks made by F. W. Clarke,[3] as the result of the statistical examination of some 700 rocks, is of interest:

Quartz	12·0
Felspars	59·5
Hornblende and Pyroxene	16·8
Mica	3·8
Accessory Minerals	7·9
	100·0

[1] The word **salic** has been coined to connote the siliceous and aluminous character: Quantitative Classification of Igneous Rocks; Chicago, 1903, p. 116. The same idea is expressed by Brögger's term **leucocratic**, which has reference to the light colour of rocks rich in *salic* minerals.

[2] The word **femic** indicates the ferro-magnesian character, and **alferric** the presence of alumina and **ferric** oxide in the minerals: *ibid.* Brögger's term **melanocratic** has reference to the dark colour of rocks rich in *femic* and *alferric* minerals.

[3] F. W. Clarke: The Data of Geochemistry; Washington, 1908.

Changes in Composition Subsequent to Consolidation.

Various changes may take place in the igneous rocks subsequent to their consolidation. They may be classified under the following heads: (1) *pneumatolytic changes*, produced by the action of gaseous exhalations which accompanied or immediately followed the intrusion of the magma; (2) those produced by percolating thermal waters (*hydrothermal metamorphism*); (3) those due to the intrusion of later igneous masses (*contact or thermal metamorphism*); (4) the crushing down and reconstruction of minerals under the influence of earth-movements (*dynamic metamorphism*); (5) and, finally, *atmospheric or meteoric weathering*.

The changes brought about by the first two and the last, consist in the decomposition of the original minerals, the formation of new minerals from the same materials, the removal or introduction of new material, etc. As far as they involve a change in the material (chemical) composition of the rock, they are known as *metasomatic*.

Pneumatolytic changes are especially evident in volcanic districts, where the gases, discharged even long after the effusion of lava has ceased, cause wide-reaching changes in the rocks they attack. The decomposition of the volcanic rocks by hydrochloric acid and sulphuretted hydrogen, together with steam, in the *solfatara* near Naples, is a well-known instance.[1]

[1] Hence the term *solfataric* activity.

The changes wrought by the gaseous emanations of the vapour vents, or *fumaroles*, of volcanoes whose activity has not long ceased, or which are in a condition of intermittent quiescence, afford another example. The gases emitted through these channels are hydrochloric and sulphurous acid, carbon dioxide, etc. They differ according to the stage of volcanic action which has been reached at the time of emission.

The effects of pneumatolysis can also be well studied in connection with certain tourmaline-bearing granite intrusions, where highly-heated water vapour, derived doubtless from the same deep-seated source as the granite itself, and containing compounds of boron and fluorine, and probably also metallic constituents, such as lithium, tin, tungsten, and uranium, has apparently modified certain portions of the granite and the sediments in its vicinity. Thus certain belts in the Cornish granites are converted into *greisen* (an aggregate of quartz and white mica), or into *schorl-rock* (quartz and tourmaline). The greisen occurs in veins, usually near the contact of the granite with the country rock. It is a completely recrystallized rock, consisting of quartz and white mica. It is assumed that the solvent vapours, which in this rock have effected the replacement of the felspar by quartz and white mica, came up through cracks which had formed in the already-solidified granite. The rock in the immediate neighbourhood of the cracks was modified in the manner described, and thus "veins" of greisen were produced. The rock which gave rise to the schorl-

rock was in some cases a porphyritic granite. The felspar crystals, however, whilst retaining their original shape, have had their substance replaced by a granular aggregate of quartz, tourmaline, apatite, and white mica. The felspar and black mica of the ground-mass have also been replaced by tourmaline and quartz. Occasionally pseudomorphs of tinstone and quartz, after felspar, are found.[1]

The so-called *kaolinisation* of granite, by which the felspathic constituent of the rock is converted into an aggregate of secondary minerals, consisting largely of hydrated silicates of alumina, but including also muscovite and quartz, is also ascribed by some to the action of heated vapours (steam, carbon dioxide and hydrofluoric acid) ascending from below through fissures in the granite.[2] Others, however, hold that this decomposition of granite is, in the main, the result of percolation of atmospheric water carrying dissolved carbon dioxide. When completely decomposed, the rock becomes so friable that it can be broken down by a stream of water, and this fact is made use of in the process by which china clay is produced.

Interesting pneumatolytic changes have been observed in the greenstones (dolerites) that are sufficiently near the granite to have been affected by its fluoric and boric emanations. These rocks being rich in lime, this substance is prominent in the composition of the newly-formed minerals. Thus axinite (boro-silicate of lime and alumina) is

[1] Reid and Flett: The Geology of the Land's End District, *Mem. Geol. Surv.*, 1907, p. 49. Rösler: *Neues Jahrb.* B.B., 1901, p. 231.

[2] Flett, *loc. cit.*, p. 58.

characteristic of the pneumatolytic veins of the greenstones. Other secondary minerals are fluorspar, epidote, pale-green augite, green hornblende, brown garnet, sphene and occasionally zinc-blende.[1] The same minerals are produced when the rocks affected are calcareous sediments.

Hydrothermal metamorphism is closely allied to pneumatolysis both in its origin and effects; and it is possible, as suggested by Harker,[2] that the circulating waters that bring it about may, in some cases, be of the same volcanic origin as the lavas whose metamorphism they subsequently effect. On this assumption a portion of the water, occluded in the magma on its eruption, did not escape in the form of vapour, but remained shut up in vesicles and other interstices of the lava. The changes brought about by the restricted circulation of such heated waters must, on this theory, be regarded as a final phase of vulcanicity. The minerals that form the amygdales of the basaltic lavas probably owe their origin to agencies of this nature. Among them may be mentioned the hydrated silicates known as zeolites; also chlorite, calcite, chalcedony, opal, and quartz. The materials which went to form these minerals were derived from the constituents of the rock, largely from the felspar, but also from the ferromagnesian and calcareous minerals.

In this connection the changes which, as Daubrée[3]

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[1] Flett, *loc. cit.*, pp. 38 and 39.

[2] The Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 41.

[3] Daubrée: *Sur le Métamorphisme*, Paris, 1860.

showed, have been produced by the alkaline thermal waters of Plombières in the Vosges, are of interest. The masonry which supported the aqueducts that conveyed the water to the Roman baths, and through which the hot waters had been percolating for centuries, was found to contain various zeolites, calcite, aragonite, fluorspar and opal. These minerals had been formed by the action of the alkaline waters on the calcareous, aluminous and siliceous materials of the masonry.

But circulating thermal waters may also be the means of introducing entirely new material from without, by which the composition of a rock may be considerably changed. Thus the percentage of silica in some of the Peru andesites has been considerably raised, subsequent to their consolidation, by the introduction of chalcedonic and opaline silica.[1] A similar "silicification" of some of the Rhenish trachytes (Rosenau in the Siebengebirge, and at Berkum near Cologne) was described by Von Lasaulx; and like phenomena have been observed among the acid volcanic rocks of Caernarvonshire and of Shap.[2]

Contact-metamorphism. With regard to changes produced in igneous rocks by the heat due to later intrusions, there is not much information available. Allport[3] has shown that the augitic greenstones (dolerites) within the contact zone of the Cornish

[1] Hatch: *Tschermak's Min. u. Pet. Mitth.*, vol. vii., p. 328.

[2] Harker and Marr: *Quart. Journ. Geol. Soc.*, vol. xlvii. (1891), p. 303.

[3] *Quart. Journ. Geol. Soc.*, vol. xxxii. (1876), p. 407.

granites, are converted into rocks in which secondary hornblende and biotite are abundant. Newly-formed augite and epidote also occur.[1] Similar phenomena have been observed in the Harz by Lossen; and the syenites of Meissen are reported to have effected the conversion of the diabasic rocks into hornblende-schists. Marr and Harker[2] have shown that the Borrowdale andesites undergo marked changes in contact with the Shap granite: the metamorphism involves the formation of brown mica, sphene, etc., in the body of the rock, while in the vesicles green hornblende is produced by the alteration of the chlorite that originally filled them.

Interesting changes as a result of contact metamorphism have been observed by Harker[3] in the Skye basic lavas, where they have been invaded by large gabbro and granite intrusions. The secondary minerals are chiefly a green fibrous hornblende, a brown biotite, and some epidote. The hornblende is derived from the augite of the original rock, while the biotite comes from chloritic and other alteration products. The felspars are little changed in the least metamorphosed rocks, but in the most altered types they are completely recrystallized. Of especial interest are the changes observed in the amygdales, for here the lime and lime-soda zeolites which filled the vesicular cavities of the lavas, are found to be

[1] The Geology of the Land's End District, *Mem. Geol. Surv.*, 1907, p. 37.

[2] *Quart. Journ. Geol. Soc.*, vol. xlvii. (1891), p. 266.

[3] The Tertiary Igneous Rocks of Skye, *loc. cit.*, p. 51

converted into lime-soda felspars. In these cases the chemical change brought about by contact metamorphism involved little more than the expulsion of the water; this process being the reversal of that by which the zeolites were derived from the felspars of the original lava under the influence of hydrothermal metamorphism.

Closely allied to the phenomena of contact metamorphism are the changes brought about in an invaded igneous rock by the *injection of the invading magma*. An example of this has been described by Professor Sollas at Barnavave, Carlingford district in Ireland,[1] where a gabbro, in which contraction-joints and fractures, due to earth movements, had been opened, has been intimately penetrated by the fluid magma of a granophyre, so as to produce a new rock of intermediate character.

The consideration of variations in the composition of a magma before consolidation, does not properly belong here; but it is convenient, while dealing with the subject of contact alteration, to refer to the changes that may be brought about in an invading magma by the *absorption of fragments* of the invaded rock. This type of contact alteration is well illustrated by the Carrock Fell rocks described by Harker.[2] In this case a *heterogenetic* or *hybrid* rock has been produced by the incorporation in a granophyre magma of highly basic portions of a gabbro. The same author has described similar

[1] *Trans. Roy. Irish Acad.*, xxx. (1894), p. 479.
[2] *Quart. Journ. Geol. Soc.*, vol. li. (1895), p. 136.

phenomena in Skye.[1] Zirkel[2] also considers the zircons and sapphires that occur in the basalt of Finkenberg, near Bonn on the Rhine, as xenocrysts (see page 28) derived from included rock fragments which, with the exception of these minerals, have been completely absorbed by the basalt. Possibly the kimberlite of the diamond pipes of South Africa, the origin of which has been so much discussed, may have been produced in a similar manner.[3] In this hybrid rock there are, besides xenoliths of a great variety of rocks, xenocrysts of numerous minerals, among the most important of which are garnet, chrome-diopside, kyanite, graphite, and diamond.

The subject of the **dynamic metamorphism** of the igneous rocks—*i.e.*, of the changes produced as a result of mechanical stress—is too wide-reaching to be adequately discussed here. It must suffice to allude to some of the commoner modifications. In many cases these are mainly structural; such as *granulation*[4] of the constituents (*e.g.*, quartz), their

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[1] The Tertiary Igneous Rocks of Skye, *loc. cit.* Harker describes on p. 192 a hybrid rock (*marscoite*) produced by the absorption of granitic material by a basic magma.

[2] *Abh. math. phys., kgl. Gesellsch. der Wissensch.*, vol. xxxviii. (1903). See also *Lehrbuch der Petrogr.*, 2nd edit., 1893, p. 593.

[3] See A. du Toit: *Eleventh Ann. Rep. of the Cape Geol. Comm.* (1906), p. 151.

[4] Granulation of this type is termed *cataclastic* in contradistinction to the *protoclastic* granulation produced by the breaking down of the earlier formed minerals, in a partially consolidated magma, under the influence of differential movement or "flow."

linear extension, the formation of *lenticular knots*, or *eyes*[1]; and the rolling out of massive igneous rocks into *mylonites*[2] and *foliated gneisses* and *schists*. But mineralogical change necessarily accompanies these mechanical processes; whether it proceeds without any essential chemical change, as when augite passes into hornblende (dolerites being converted into epidiorites and hornblende schists); or involves the breaking down of complex silicates and the building up of simpler compounds from the materials thereby produced. Thus the complex felspars of the igneous rocks are replaced by aggregates of quartz, albite, and muscovite (sericite); while epidote, zoisite, rutile, sphene, and chlorite are formed partly from the felspathic and partly from the ferro-magnesian constituents.

The changes due to weathering are mainly brought about by the percolation of surface waters carrying in solution the atmospheric gases (carbon dioxide, etc.). During the first stage of alteration the felspars and felspathoids, originally clear and glassy, become turbid, being converted to an aggregate of sericite (muscovite), kaolin, quartz or calcite; while the ferro-magnesian minerals yield chlorite, serpentine, and talc, with separation of iron-oxides. If the rock is glassy, it becomes dull and stony, or, in the case of the basic glasses, is converted by hydration into the brown or yellow substance known as palagonite. By changes such as these olivine and hornblende rocks give rise to serpentines, quartz-

[1] As in *Augen-gneiss*.

[2] From the Greek for a mill.

porphyries and rhyolites to felsitic rocks, andesites to propylites, etc.

By continued weathering the alteration is carried to a still further stage: the rocks lose their alkalies, a large part of their lime, and a variable proportion of their silica and iron. The final product is a decayed clayey mass, consisting largely of a hydrated silicate of alumina and iron (*wacke, laterite, plinthite, bole, lithomarge, ochre,* etc). In a few cases, the further removal of silica leaves a substance consisting practically of hydrated alumina (*bauxite*).

PART II.

THE CONSTITUENT MINERALS OF THE IGNEOUS ROCKS.

CHAPTER I.

CLASSIFICATION OF THE ROCK-FORMING MINERALS.

The rock-forming minerals may be variously classified, according to the part played by them in the structure and composition of rocks. A useful division is into essential and accessory. An **essential** mineral is one whose presence is implied in the definition of the rock. An **accessory** mineral is one whose presence or absence does not sensibly affect the character of the rock. Thus, quartz, felspar and mica are essential constituents of granite; while zircon, sphene and apatite are accessory.

The accessory minerals may be further sub-divided into those of original and those of secondary origin. They are termed **original** when they came into existence with the rock of which they form part, or when they existed before it. They are **secondary**

when they result from the alteration or reconstruction of the original minerals (by weathering, contact and dynamic metamorphism, etc.). In altered rocks an essential mineral may be replaced by a secondary one.

Law of Decreasing Basicity.

The rock-forming minerals are divided by Rosenbusch into four groups according to the law of decreasing basicity, formulated by him.

1. The ores and accessory constituents (magnetite, hæmatite, ilmenite, apatite, zircon, spinel and sphene).
2. The ferro-magnesian constituents (biotite, hornblende, pyroxene and olivine).
3. The felspathic constituents (felspar, nepheline, leucite, melilite, sodalite and haüyne).
4. Free silica.

As expressed by Rosenbusch, "*the order of consolidation of the silicates and, consequently, their crystallographic development (idiomorphism) correspond to a law of decreasing basicity; the ores and accessory minerals are the earliest, and quartz is the latest, product of the rock-forming process.*" This law expresses in general the facts observed with regard to the majority of rocks, but it does not hold in the case of the most acid or of the most basic rocks. The members of the first group separate earlier than those of the other groups; but while in granites and syenites the members of the second group precede those of the third, in dolerites and gabbros the reverse order holds good.

Classification by Colour in Thin Section.

In the following list the chief minerals are classified into essential, accessory and contact minerals, with further subdivision of the accessory minerals into original and secondary. The arrangement according to colour in thin sections must not be taken too strictly; minerals which, when free from inclusions and unaltered, are colourless, derive colour from the presence of a small quantity of some foreign body, or become stained by decomposition. The intensity of colouration is, of course, proportional to the thickness of the section.

1. Essential.

Quartz. Felspars. Felspathoid minerals. Light micas. Olivine.	Colourless.
Amphiboles. Pyroxenes (sometimes colourless). Dark micas.	Coloured.

2. Accessory.

(*a*) *Original.*

Sodalite. Haüyne and Nosean. Melilite. Scapolite. Apatite	Colourless, or slightly coloured.

Analcime.	Colourless, or slightly coloured (*continued*).
Zircon.	
Eudialyte.	
Cordierite.	
Garnets.	
Spinels.	Coloured.
Tourmaline.	
Sphene.	
Xenotime.	
Monazite.	
Magnetite.	Opaque.
Ilmenite.	
Pyrites.	

(*b*) *Secondary.*

Quartz, Opal, Chalcedony.	Colourless, or slightly coloured.
Felspar.	
Carbonates (Calcite, Dolomite, etc.).	
Zeolites.	
Kaolinite.	
Fluorspar.	
Talc.	
Muscovite (Sericite).	
Zoisite.	
Epidote.	Coloured and opaque.
Sphene (Leucoxene).	
Tourmaline.	
Chlorites.	
Serpentine.	
Hornblende (Uralite).	
Iron-Ores (Magnetite, Pyrites, etc.).	

3. Contact Minerals.

The following minerals are developed in sedimentary rocks within the aureoles of contact-metamorphism :—

(*a*) *In Slates and Shales* (*Aluminous Minerals*).

Andalusite.
Chiastolite.
Kyanite.
Sillimanite.
Staurolite.
Cordierite.
Tourmaline.
Garnet.
Topaz.
Mica, Ottrelite, Chloritoid, etc.

(*b*) *In Limestones* (*Calcareous Minerals*).

Idocrase (Vesuvianite).
Scapolite (Dipyre and Couseranite).
Garnet (Grossularia, Essonite and Almandine).
Tremolite (a variety of Hornblende).
Salite, Malacolite, Diopside (varieties of Pyroxene).
Wollastonite.
Mica.
Sphene.
Perovskite.
Axinite.

CHAPTER II.

APPEARANCE UNDER THE MICROSCOPE.

With regard to the appearance of the rock-forming minerals in thin sections under the microscope, we must take into consideration variations in (1) External contour or form, (2) Internal or micro-structure, (3) Double refraction.

External Contour or Form.

Shape. If the conditions that prevailed during the consolidation of the rock have been such as to allow of the free growth of crystals, the minerals are bounded on all sides by crystallographic contours: in other words, they are idiomorphic. If, on the other hand, the minerals have had to struggle for existence, so to speak, they will have naturally hindered one another in their crystallographic development, and the result is an aggregate of grains bounded by allotriomorphic contours. Sometimes a mineral, which doubtless originally possessed crystallographic form, owes its present irregular fretted outline to the corrosion of the molten magma in which it floated prior to solidification. Thus the porphyritic quartz grains of the acid rocks are usually rounded and even

hollowed out by the magma. Again, the ferro-magnesian minerals (hornblende and mica) of the andesites and basalts often present peripheral "zones of corrosion" in which iron-oxides have separated out. Incipient or abortive forms (crystallites, microlites, skeleton-crystals, etc.) frequently occur in vitreous rocks where the solidification has been too rapid to permit of full crystallographic development. (See Fig. 26.)

Index of refraction. The greater the difference between the index of refraction of a mineral and that

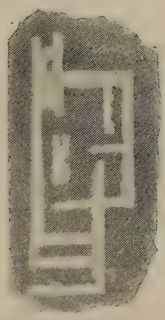

FIG. 26.
Skeleton-crystal of Felspar.

of the material in which it is embedded, the more strongly marked will be its bounding edge. Thus grains of quartz, of which the index of refraction is 1·55, are scarcely visible in Canada balsam (1·54), while augite (1·72), hornblende (1·65) and olivine (1·68) stand out boldly in this medium. The contours of minerals possessing a still higher index of refraction, such as garnet (1·78), sphene (1·89) and rutile (2·76),

appear as broad dark borders, in consequence of the large amount of light that undergoes total reflection at the bounding surface.

THE MEAN INDEX OF REFRACTION OF ROCK-FORMING MINERALS.

Rutile	2·61	Tourmaline	1·63
Anatase	2·52	Melilite	1·63
Perovskite	2·38	**Actinolite**	1·62
Chromite	2·10	Calcite	1·60
Zirkon	1·95	**Muscovite**	1·59
Sphene	1·93	Talc	1·59
Garnet	1·81	Anorthite	1·58
Ægirine	1·79	Chlorite	1·58
Epidote	1·72	**Serpentine**	1·57
Kyanite	1·72	Biotite	1·56
Spinel	1·72	Kaolinite	1·54
Zoisite	1·70	**Quartz**	1·55
Diopside	1·68	Oligoclase	1·54
Olivine	1·68	**Nepheline**	1·54
Axinite	1·68	Cordierite	1·54
Enstatite	1·67	Albite	1·53
Hornblende	1·64	**Orthoclase**	1·52
Andalusite	1·64	Sodalite	1·48
Apatite	1·63	**Fluorspar**	1·43

THE INDEX OF REFRACTION OF VARIOUS MEDIUMS USED IN THE DETERMINATION OF THE REFRACTION OF MINERALS.

Water	1·333	Monobrombenzol	1·561
Olive oil	1·469	Bromoform	1·588
Beech-nut oil	1·477	Cinnamon oil	1·605
Cedar oil	1·516	Monochlornaphthalene	1·635
Canada balsam	1·540	Monobromnaphthalene	1·655
Clove oil	1·542	Methylene iodide	1·740

Internal or Micro-Structure.

The principal variations in the micro-structure of the rock-forming minerals in thin section and mounted in Canada balsam, are those produced by surface-relief, by cleavage and by foreign inclusions.

Surface-relief. The unevenness of the surface of a mineral ground to a thin section, is only noticeable when there is a considerable difference between the index of refraction of the mineral and that of the medium in which it is mounted. Minerals with a high index of refraction, like olivine and sphene, for instance, have a dappled or mottled appearance, that is absent from minerals like quartz and felspar of which the index of refraction approximates to that of Canada balsam. It is to be noted that the apparent relief of calcite, which has indices of refraction lower and higher than Canada balsam, changes when the section is rotated in polarised light.

Cleavage. The lines of division of a mineral show greater or less distinctness, precision and regularity, according to the degree of perfection of the cleavage. A perfect cleavage gives numerous fine straight lines, while an imperfect one gives lines which are branching and irregular in proportion to the difficulty of separation. The distinctness and thickness of the cracks depend also on the difference between the index of refraction of the mineral and that of the Canada balsam in which it is mounted. Thus the cracks in quartz and the cleavages in felspar are much less noticeable than those in olivine, augite or hornblende. The relative position of cleavage lines depends on the

direction of the section through the mineral. A prismatic cleavage produces two intersecting sets of parallel lines, unless the section be in the direction of the vertical axis, in which case the two sets coincide. A basal or pinacoidal cleavage furnishes only one set of lines.

Inclusions. During their formation, crystals take up and inclose portions of the matrix from which they have separated, and other foreign bodies. These

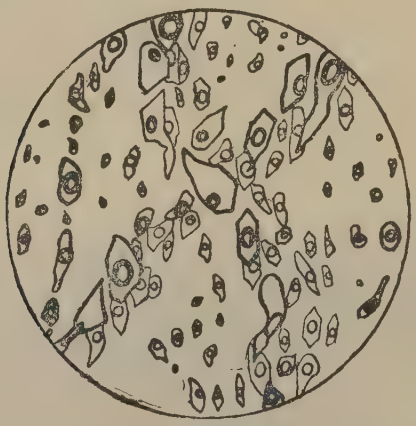

FIG. 27.
Highly magnified Liquid Inclusions in Quartz.
(*After Fouqué and Lévy.*)

inclusions may bear a definite crystallographic relation, in their arrangement, to the shape of the crystal (*i.e.*, they may be *central*, *peripheral*, or *zonal*), or they may be distributed without definite arrangement. They are of four kinds:—(1) gaseous, (2) liquid, (3) glassy and (4) mineral. *Gas-inclusions*

are small, round, or elliptical cavities filled with air or carbon dioxide. Occasionally they have the inverse shape of their host, being, in fact, negative crystals. In consequence of the difference in refractive index between the gas and the mineral substance inclosing it, gas-inclusions are always bounded by a well-marked dark border. *Liquid-inclusions* are also round, elliptical, or tubular bodies, having a contour somewhat less strongly marked than that of

FIG. 28.
Crystal of Augite, containing a vitreous core.

gas-inclusions. The liquid, which may consist of water or carbon dioxide under pressure, usually does not quite fill the cavity, and a small movable bubble remains. When sufficiently small, the bubble possesses a constant vibratile motion. The water is sometimes saturated with common salt, and may then contain cubic crystals of that mineral. Liquid-inclusions occur abundantly in many minerals, not-

ably in quartz. (See Fig. 27.) *Glass-inclusions* are distinguished from liquid-inclusions by the sharpness of their contours and the fixity of their bubble; also by the fact that more than one bubble is frequently present. The inclosed glassy substance is often coloured or turbid, being related in this respect to the glassy base of the rock. (See Fig. 28.)

FIG. 29.

Glass Inclusions with bubbles and crystallites, highly magnified. (*After Fouqué and Lévy.*)

Devitrification, or the development of crystallites and microlites, may also have taken place. *Mineral-inclusions* are distinguished from the foregoing by the possession of idiomorphic contours. They may consist of needles, rods, granules, plates or scales, and are often arranged along planes bearing a definite relation to the symmetry of the crystal in which

they are included, being then often the cause of the optical phenomena known as *schiller, chatoyancy* and *asterism.*

Double Refraction.

All doubly refractive minerals are coloured between crossed nicols, the colouration being a result of the *interference* of the two rays that are produced by the passage of light through such minerals. The *degree* of colouration (*i.e.*, in Newton's scale of colours) depends on the amount of separation of the two rays, and this varies with the thickness of the section for any given mineral, or, the thickness being constant, with the nature of the mineral experimented upon. Thus, in sections of such thickness that the felspar gives a grey between crossed nicols, quartz will give a yellow of the first order, and augite and hornblende, bright blues, greens and reds of the second and third orders.

The following figures, representing the maximum birefringence of some well-known minerals, form a useful scale for the comparison of the double refraction colours in thin sections *of a uniform thickness.*[1]

[1] It is beyond the scope of this book to deal with the optical determination of minerals under the microscope. For information on this subject reference may be made to Rock Minerals, by J. P. Iddings, New York, 1906; to Minerals in Rock Sections, by Luquer; to Anleitung zur Gebrauch des Polarisationsmikroskop, by Dr. E. Weinschenk, Freiburg im Breisgau, 1906; or to Kurze Anleitung zur mikrosk. Krystalbestimmung, by Schroeder van der Kolk, Wiesbaden, 1898. Messrs. Swift & Sons of London supply a microscope, suitable for petrological work, at a moderate price.

THE MAXIMUM BIREFRINGENCE OF SOME ROCK-FORMING MINERALS.

Rutile	·287	Very strong.
Magnesite	·202	
Dolomite	·179	
Calcite	·177	
Aragonite	·155	
Sphene	·091	
Zircon	·062	
Talc	·050	
Muscovite	·043	
Epidote	·038	Strong.
Olivine	·035	
Orthite	·032	
Actinolite	·027	
Augite	·025	
Sillimanite	·020	
Diopside	·018	
Hornblende	·016	
Wollastonite	·015	
Hypersthene	·012	Moderate.
Andalusite	·011	
Gypsum	·010	
Quartz	·009	
Orthoclase	·008	
Zoisite	·006	Weak.
Nepheline	·005	
Apatite	·003	
Leucite	·001	
Pennine (Chlorite)	·001	

CHAPTER III.

DESCRIPTION OF THE ROCK-FORMING MINERALS.

SILICA GROUP.

Quartz. Pure silica, SiO_2. Crystallizes in the rhombohedral system, the crystals being usually bounded by the hexagonal prism (recognisable by its horizontal striations) with pyramidal (rhombohedral) terminations. Sometimes, however, the prism faces are absent, the crystals then consisting of the double pyramid of twelve faces. Unattacked by acids, excepting hydrofluoric acid. Insoluble in potash (distinction from opaline silica). Sp. G. = 2·6. Hardness = 7.[1]

Index of refraction, 1·551. Double refraction, moderate. Between crossed nicols the polarization-colours vary, in moderately thin sections, between a light grey and pale yellow of the first order of

[1] Mohs' scale, viz., 1 = talc ; 2 = gypsum ; 3 = calcite ; 4 = fluorspar, 5 = apatite, 6 = orthoclase, 7 = quartz, 8 = topaz, 9 = corundum, 10 = diamond. If the hardness of corundum be represented by 1,000, then, according to Jaggar, the hardness of the other minerals composing Mohs' scale may be expressed by the following figures : topaz, 152 ; quartz, 40 ; felspar, 25 ; apatite, 1·23 ; fluorite, ·75 ; calcite, ·26 ; gypsum, ·04.

Newton's scale of colours. Thicker sections, of course, show brighter colours (yellow, red, blue, etc.). Sections perpendicular to the vertical (here coincident with the optic) axis give a uniaxial interference-figure.

Quartz may be recognised by its hardness, pellucidity, vitreous lustre and irregular to sub-conchoidal fracture. Usually it is colourless, sometimes, however, brownish or yellowish (*smoky quartz, cairngorm,*

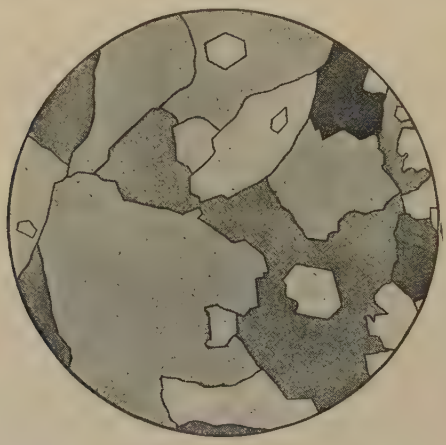

FIG. 30.
Secondary quartz-aggregate; between crossed nicols.
(*After Lindgren.*)

etc.), pink (*rose quartz*), purple (*amethyst*) or bluish (in certain gneisses and in some Palæozoic and pre-Cambrian grits). Under the microscope it appears in clear, colourless grains, characterised by the presence of innumerable minute liquid-inclusions generally arranged along lines and planes. High magnifica-

tion discloses in many of these a minute vibratile bubble, occasionally also cubes of salt, showing that the liquid, in some cases at least, consists of a saturated solution of that substance. In other cases, the enclosed substance has been proved to be carbon dioxide.

Quartz is the mineral eminently characteristic of the acid rocks. In granites and tonalites it occurs in irregular grains without definite crystalline contours; and in microgranites, felsites and rhyolites, in rudely-contoured, often bipyramidal crystals, which are, however, generally corroded by the surrounding magma. As a secondary constituent, quartz fills cracks, joints and cavities (*vein-quartz*); similarly it occurs in association with felspar, mica, tourmaline, etc., in the so-called pegmatite-veins.

Tridymite. Pure silica, SiO_2. Triclinic, but affecting hexagonal symmetry. In thin, six-sided, colourless tablets, which split up between crossed nicols into a number of depolarizing areas, showing light and dark banding. Insoluble in acids; soluble in alkalies. Sp. G. = 2·3. Hardness = 7. Index of refraction, 1·477. Tridymite occurs in volcanic rocks (rhyolites, trachytes and andesites), lining their cavities with pretty groups of interpenetrating twins and trins: a well-known occurrence is in the rhyolite of Tardree, Antrim. Under the microscope it is described as occurring in imbricated aggregates. Tridymite is only found in lavas, and appears to have been produced under the influence of some mineralizing agent.

Opal. Hydrated silica: $SiO_2 + Aq$. This mineral occurs in amorphous masses resulting from the solidi-

fication of colloid or hydrated silica. Colour variable: yellow, brown, etc. Translucent to opaque. Soluble in alkalies (distinction from quartz). Sp. G. = 2·2. Hardness = 5·5–6. Index of refraction = 1·45.

Opal is a secondary constituent of many acid volcanic rocks (rhyolites, trachytes, and even the less acid andesites). It is also deposited from the

FIG. 31.

Spherulitic Opal in a chalcedonic matrix, between crossed nicols. *(After Fouqué and Lévy.)*

water of hot springs and geysers (*geyserite*). *Hyalite*, a pure colourless variety, frequently occurs in andesites. Between crossed nicols opal is usually isotropic, but occasionally shows weak double refraction. A black cross between crossed nicols is observable in spherulitic opal. (See Fig. 31.)

Chalcedony. Silica, SiO_2. Mixtures of crystal-

line and amorphous silica. Cream-coloured to colourless; translucent to semi-opaque. Insoluble in acids; partially soluble in alkalies. Sp. G. = 2·59 – 2·64. A common secondary constituent of igneous rocks. Under the microscope chalcedony has a fibrous structure, giving an imperfect black cross between crossed nicols.

Agate consists of alternating layers of chalcedony, jasper, amethyst and other varieties of silica. It is found filling wholly, or partially, the amygdaloidal cavities of old vesicular lavas (melaphyre, basalt, etc.).

FELSPAR GROUP.

The felspars crystallize in two systems, the monoclinic and the triclinic; but the forms of the two systems are very similar, and the angles between analogous faces differ by a few degrees only.

The chief *monoclinic* felspars are orthoclase and sanidine. *Triclinic* are microcline, albite, oligoclase, andesine, labradorite, bytownite and anorthite. The felspars of the albite-anorthite series are comprised under the general term plagioclase.

The commonest combination of faces presented by the felspars consists of the following forms: the basal plane (generally denoted by P), the clino- or the brachy-pinacoid (M), the prisms (T and l), the two ortho- or the two macro- domes (x and y), the clino- or the brachy-dome (n), and the pyramid (o) (Fig. 32).

The principal cleavage is basal (P); but this is nearly equalled by the cleavage parallel to M. These

two cleavage planes are at right angles in orthoclase, but are inclined to one another at less than a right angle in the triclinic felspars. Under the microscope orthoclase presents sections that are uniformly affected by polarized light, or are divided into two areas that present uniform polarization respectively (dual

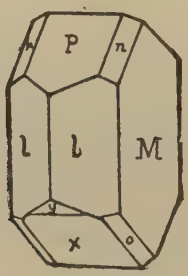

FIG. 32.
Crystal of Orthoclase.
P. Basal plane.
M. Clinopinacoid.
l. Prism.
x and *y*. Orthodomes.
o. Pyramid.
n. A clinodome.
(*After Rosenbusch.*)

twinning on the Carlsbad type); whereas plagioclase usually has a striated appearance between crossed nicols, due to the different angles of extinction of alternating twin lamellæ (polysynthetic twinning on the albite type).

1. Alkali-Felspars.

Orthoclase, or potash-felspar. Chem. comp. = K_2O, Al_2O_3, $6SiO_2$ (65% SiO_2, 17% K_2O and 18%

Al_2O_3). Monoclinic. Sp. G. = 2·54-2·57. Hardness = 6. Index of refraction, 1·524; double refraction, moderate; it is distinctly less than quartz, sections of ordinary thickness polarizing in grey colours between crossed nicols. Unattacked by acids except hydrofluoric acid. Two types of crystal are common :—flat tables (with *M* largely developed) and stout prisms. A roof-like

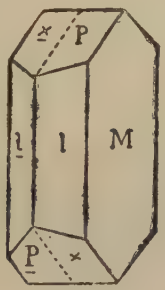

FIG. 33.
Orthoclase Crystal twinned on the Carlsbad-type.
P. Basal plane.
M. Clinopinacoid.
l. Prism.
x. An orthodome.
(*After Rosenbusch.*)

termination is produced by the basal plane (*P*) and the orthodome (*x*), which are about equally inclined to the vertical axis, and form with one another an angle of 129° 43′. (See Fig. 32.) The crystals present dual twinning on various types (Carlsbad, Manebach, Baveno, etc.), the commonest being the Carlsbad. When twinned on this type, the crystals are usually united on the clinopinacoid (*M*), the

basal planes (P) of the crystals being inclined in opposite directions. (See Fig. 33.) Twinning of this nature is often revealed in thin sections by the difference in extinction shown by the two halves of a crystal when rotated between crossed nicols. In the Manebach type the twinning-plane is the basal plane (P); in the Baveno type it is the clinodome (n).

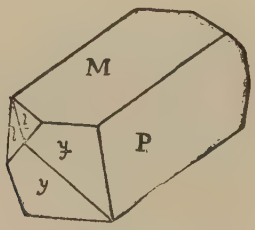

FIG. 34.

Crystal of Orthoclase twinned on the Baveno-type.

P. Basal plane.
M. Clinopinacoid.
l. Prism.
y. An orthodome.
(*After Rosenbusch.*)

Orthoclase occurs pure and colourless in the variety termed **adularia**. Usually, however, it is turbid and cloudy, due to the development of various decomposition products. This decomposition of felspar, which is loosely spoken of as *kaolinization*, consists in the formation of hydrated silicates of alumina, with liberation of free silica, and removal of the alkalies. Among the secondary minerals thus produced the sericite variety of mica is easily recognised;

the presence of kaolinite is not so easily demonstrable, although there can be little doubt that it is also formed.

Orthoclase occurs as a constituent of the more acid plutonic and older volcanic rocks (granite, syenite, felsite), often in large well-developed crystals (granite-

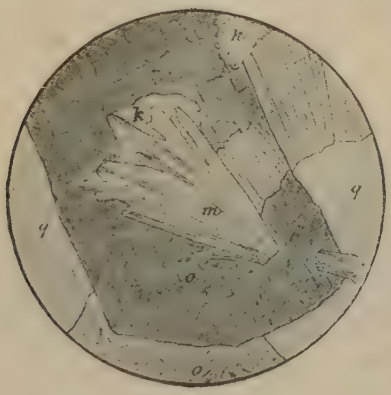

FIG. 35.

Orthoclase Felspar, with decomposition products.

o. Orthoclase.
q. Quartz.
m. Secondary muscovite.
k. Kaolin.

porphyry, felspar-porphyry); also in foliated rocks (gneiss and various schists); and, together with quartz and other minerals, in segregation veins (pegmatites). Among the sedimentary rocks it occurs in the so-called felspathic grits or arkoses, which are derived from the disintegration of granitic rocks.

Sanidine is the name given to a clear, glassy, fissured variety of orthoclase occurring in the more recent acid lavas (rhyolite, trachyte, obsidian). It usually occurs in flat tables, twinned on the Carlsbad type; also in prismatic crystals and irregular grains. Under the microscope it is distinguished from orthoclase by its pellucidity. Inclusions (glass, etc.) are, however, common. The crystals have often under-

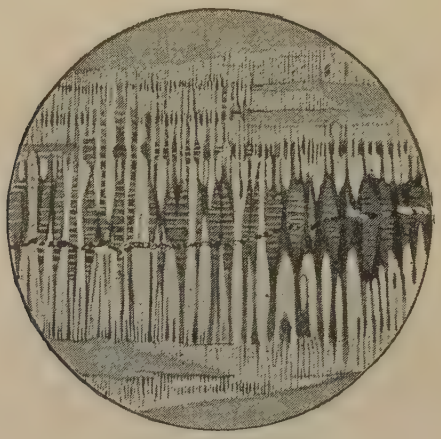

FIG. 36.
Section of microcline, under the microscope.

gone fracturing and corrosion during the eruption of the lava in which they were suspended.

Microcline is a triclinic potash-felspar, with pseudo-monoclinic symmetry, being very nearly allied in external form to orthoclase. The angle formed by the basal and the clinopinacoidal cleavage planes is very nearly, but not quite 90° (actually

89° 50′). It is distinguishable from orthoclase, however, by a characteristic cross-hatching that becomes visible when the mineral is viewed between crossed nicols. This structure is generally ascribed to intersecting systems of twin-lamellæ, parallel and perpendicular to the edge *PM*; it is characterised, however, by the fact that the lamellæ are spindle-shaped, instead of being bounded by

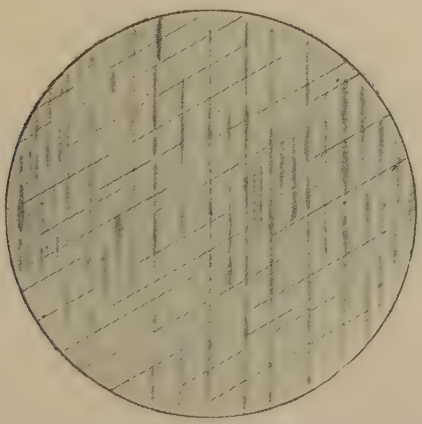

FIG. 37.
Perthite : section parallel to the clinopinacoid.

parallel edges. (See Fig. 36.) The extinction angle of microcline is 15° 30′ measured to the edge *PM*.

Perthite. Both orthoclase and microcline are often intergrown with a soda-felspar (albite or oligoclase). The latter occurs in narrow lamellæ intercalated along planes parallel to the orthopinacoid. In sections

parallel to the basal plane or clinopinacoid the included felspar appears in patches and strips, which are distinguishable from the main mass of the orthoclase or microcline by their twin-striation or by their different extinction-angle. Such admixtures are known as perthite, micro-perthite, or microcline micro-perthite.

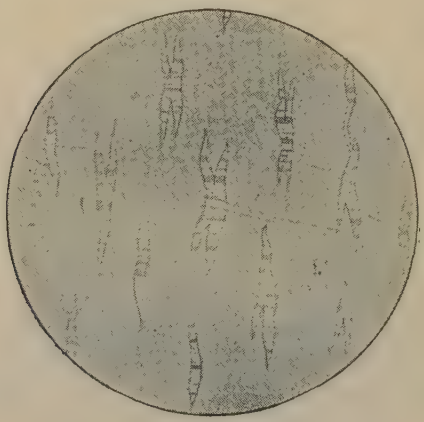

FIG. 38.
Perthite: section parallel to the basal plane.

Considered chemically, the felspars are silicates of alumina and one or more of the bases potash, soda and lime. There are three primary felspar molecules: potash-felspar $\frac{1}{2}(K_2O, Al_2O_3, 6SiO_2)=Or$; soda-felspar $\frac{1}{2}(Na_2O, Al_2O_3, 6SiO_2)=Ab$; and lime-felspar $(CaO, Al_2O_3, 2SiO_2)=An$. They occur in nature as orthoclase, albite and anorthite respectively. By their combination in definite proportions two important

series of felspars are formed: a *lime-soda* series and a *potash-soda* series. The lime-soda series comprises the well-known members: oligoclase, andesine, bytownite and labradorite. The potash-soda series is represented by felspars that have been variously described as perthite or micro-perthite, microcline micro-perthite, soda-orthoclase or crypto-perthite, and soda-microcline or anorthoclase. Soda-orthoclase (the *natron-orthoklas* of Förstner) is apparently a homogeneous mineral consisting of two orthoclase molecules in combination with three albite molecules, whereas micro-perthite, which has the same chemical composition, is a mechanical mixture of the two different felspars in intimate intergrowth (See p. 38) Brögger, however, regards soda-orthoclase as crypto-perthite, that is to say, as ultra-microscopic perthite, and ascribes its peculiar blue schiller to internal reflection from the minute planes of fracture between alternating fine lamellæ of albite and orthoclase parallel to the orthodome (*y*). The crystals have an unusual form, due to the predominance of the prisms (*T* and *l*) and the orthodome (*y*). Anorthoclase Brögger regards as a soda-microcline, and like that mineral it is referred to the triclinic system. In the same manner as he regards soda-orthoclase as crypto-perthite, so he regards soda-microcline as a crypto-perthitic modification of microcline, that is, an ultra-microscopic microcline-perthite, in which the albite lamellæ are too minute for recognition under the microscope.

2. Lime-Soda Felspars.

The lime-soda felspars are collectively known as **plagioclase**. They crystallize in the triclinic system. The crystal form is similar to that of orthoclase, with the difference that the basal plane (*P*) instead of being normal to the brachypinacoid (*M*) is inclined to it (from left to right) at an angle of 86°–87°. The distinguishing character of the triclinic felspars is the lamellar or polysynthetic twinning. The fine lineations produced by

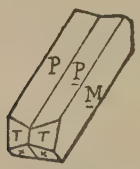

FIG. 39.

Crystal of Plagioclase twinned on the Albite-type.
P. Basal plane.
M. Brachypinacoid.
T. Prism.
x. A macrodome.
(*After Rosenbusch.*)

FIG. 40.

Repeated twinning on the Albite-type.
P. Basal plane.
M. Brachypinacoid.
(*After Rosenbusch.*)

this type of twinning can be easily seen with the pocket lens on the faces of the basal cleavage. In thin section, between crossed nicols, the twinning appears as a parallel striation, consisting of light and dark bands, due to the simultaneous extinction of alternate lamellæ. Usually the striation is parallel

to the brachypinacoid (M): this constitutes the *albite type* of twinning. (See Figs. 39 and 40.) A second series of twin-lamellæ sometimes crosses these at right angles, constituting the *pericline type* of twinning.

The researches of Tschermak, and of Day and Allen,[1] have shown that the members of the lime-soda series may be regarded as isomorphous mixtures of albite and anorthite in varying proportions. They

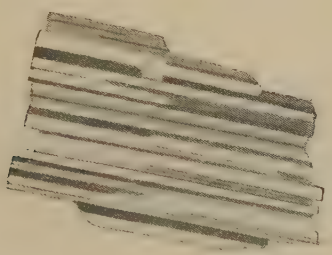

FIG. 41.
Section of twinned Plagioclase between crossed nicols.

form a graduated series both with regard to their chemical constitution and their optical and other physical properties (specific gravity, etc.). It is convenient to make use of the names oligoclase, andesine, bytownite and labradorite, to fix certain points in the series. If we represent the soda-felspar molecule $\frac{1}{2}(Na_2O, Al_2O_3, 6SiO_2)$ by Ab, and the lime-felspar molecule $(CaO, Al_2O_3, 2SiO_2)$ by An, then the inter-

[1] *Amer. Journ. Sci.*, 1905, p. 93.

mediate felspars have the composition represented by the following average formulæ and percentages :—[1]

Name.	Formula.	Percentage Composition.			
		SiO_2	Al_2O_3	Na_2O	CaO
Albite	Ab	68·7	19·5	11·8	0
Oligoclase	Ab_3An_1	62·0	24·0	8·7	5·3
Andesine	Ab_2An_1	60·2	25·2	7·9	6·7
Labradorite	Ab_1An_1	55·6	28·3	5·7	10·4
do.	Ab_1An_2	51·7	30·9	4·0	13·4
Bytownite	Ab_1An_5	47·4	33·8	2·0	16·8
Anorthite	An	43·2	36·7	0	20·1

With regard to the optical properties of the plagioclases, the extinction angles are smaller for the soda end of the series (albite, oligoclase and andesine) than for the lime end (labradorite and anorthite). In general, a high extinction-angle may be taken as indicating a felspar of the basic (or lime) end of the series; while a low extinction-angle indicates a felspar of the albite, oligoclase, or andesine type. Microlites consisting of a felspar intermediate in composition between oligoclase and andesine, extinguish straight. The double refraction is moderate.

The specific gravity and optical properties of the different members of the series are summarised in the following table:

[1] Since the rate of the molecular weight of Ab to An is as 1:1·061, it is approximately accurate to calculate the relative weight of the two felspar substances in the proportion of the number of molecules: thus $Ab_3An_2 = \frac{3}{5}$ by weight of Albite to $\frac{2}{5}$ Anorthite.

Name	Formula	Sp. G.[1]	Mean Index of Refraction	Extinction-angles in sections normal to (010)(001):
Albite	Ab	2·605	1·535	−15°
Oligoclase	Ab_3An_1	2·649	1·545	+5°
Andesine	Ab_2An_1	2·660	1·549	14°
Labradorite	Ab_1An_1	2·679	1·558	28°
do.	Ab_1An_2	2·710	1·567	37°
Bytownite	Ab_1An_5	2·733	1·577	41°
Anorthite	An	2·765	1·585	43°

The plagioclase felspars usually contain numerous inclusions: liquid, glass and mineral matter (hæmatite, rutile, mica, etc.). These may be irregularly distributed, or arranged along certain crystallographic planes, or in zones parallel to the periphery of the crystal. A different kind of zonary structure is that produced by the presence of felspar layers, marking a gradual change of composition in the crystal during its growth. The chemical analysis of a felspar is therefore not always made on homogeneous material, as the outermost layers of a crystal may have quite a different composition to the central core.

The following minerals result from the decomposition of basic plagioclases: epidote, zoisite, albite (in the so-called saussurite) and calcite.

Albite, oligoclase and andesine are not attacked by hydrochloric acid; labradorite is to a small extent; while anorthite is decomposed with separation of gelatinous silica. The fusibility is greatest in albite,

[1] From determinations made by Day on artificially prepared felspars.

and decreases with the diminution of soda and the increase of lime. The specific gravity, on the other hand, is least at the soda end and greatest at the lime end (see table on page 97).

Just as orthoclase is characteristic of the acid rocks, so the different plagioclase felspars are found in rocks of intermediate and basic composition: oligoclase and andesine occur in the diorites, porphyrites and andesites; labradorite in gabbros, dolerites and basalts; and anorthite in allivalite, eucrite, etc. Oligoclase also accompanies orthoclase in many granites and trachytes. Albite is frequently present as a secondary constituent ("secondary felspar") in the so-called felspar-quartz mosaic of mechanically metamorphosed rocks. Its clear unstriated granules are scarcely distinguishable from quartz, but for the fact that they give a *biaxial* interference-figure in convergent polarized light.

THE FELSPATHOID GROUP.

Nepheline. Silicate of soda, potash and alumina: $(NaK)_2O, Al_2O_3, 2SiO_2$. Pure sodium-nepheline which has been prepared artificially has the composition: $SiO_2 = 42{\cdot}3$ $Al_2O_3 = 35{\cdot}9$, $Na_2O = 21{\cdot}8$, but in nepheline as it occurs naturally the proportion of Na_2O to K_2O is usually about 5:1. Crystallizes in the hexagonal system. Occurs in small colourless and glassy six-sided prisms (combination of hexagonal prism and basal plane). Soluble in hydrochloric acid with separation of gelatinous silica; the solution giving cubes of common salt when evaporated. Sp. G. = 2·6; hard-

ness, 5·5–6. Index of refraction, 1·54. Imperfect basal and prismatic cleavage. Nepheline is found in the cavities of ejected blocks (Monte Somma, Lake Laach); as an essential constituent of certain lavas (phonolite, nepheline-basalt, tephrite, etc.); and as a constituent of the soda series of the plutonic rocks (syenites and alkali-gabbros).

Under the microscope it presents hexagonal and four-sided sections; but occurs more frequently in small colourless granules, the presence of which can often only be demonstrated by gelatinization with hydrochloric acid and subsequent staining with fuchsine. The four-sided sections extinguish straight between crossed nicols; while the six-sided ones give a uniaxial interference figure in convergent light. The double refraction is weak, the polarization colour never exceeding a grey tint in sections of normal thickness. It lies between apatite and zoisite in this respect.

This mineral is peculiarly subject to alteration, usually to zeolitic products, such as natrolite and hydro-nephelinite; also to white mica (gieseckite) or to cancrinite.

Nepheline is liable to be confused with apatite. The latter mineral, however, occurs usually in longer needles than nepheline, and has a higher index of refraction. Chemically, apatite may be distinguished by the phosphate-test from nepheline, and nepheline by gelatinization and staining with fuchsine from apatite.

Elæolite is the name sometimes given to a dull grey or greenish variety of nepheline. It forms irregular masses of considerable size, somewhat re-

sembling quartz, from which it may be distinguished by its characteristic greasy lustre and brownish colour.

Leucite. Silicate of alumina and potash: K_2O, Al_2O_3, $4SiO_2 = SiO_2$, 55·0; Al_2O_3 23·5; K_2O, 21·5.

Regular, the usual form being that of the icositetrahedron. Colour, dirty white or grey. Attacked slowly by hydrochloric acid with separation of silica. Sp. G. = 2·45 – 2·5. Hardness = 5·5 – 6. Index of refraction, 1·508. Fusible with difficulty.

Leucite occurs as a constituent of the more recent volcanic rocks: leucitophyre, leucito-tephrite and leucitite; also in members of the alkali series of the plutonic rocks.

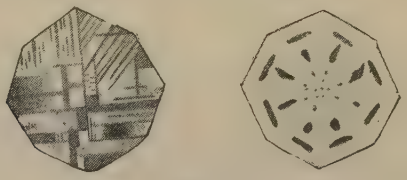

FIG. 42.

Sections of Leucite, showing the double refraction and inclusions.

Under the microscope it presents colourless polyhedral (usually eight-sided) sections. Weak double refraction, due to the mineral being in a state of strain: the larger individuals present intersecting systems of alternately light and dark twin-lamellæ. When heated to 500° C. leucite becomes normally isotropic. Inclusions (glass, magnetite, belonites, etc.) are common, showing both a zonal and a radial arrangement.

Remarkable pseudomorphs of orthoclase and nepheline after leucite have been described by Hussak, Derby, J. F. Williams, Teall, Shand, and Knight.[1] These *pseudo-leucites*, as they are called, whilst maintaining more or less the icositetrahedral form of leucite, have had their leucite substance replaced by an aggregate of orthoclase and nepheline (see Fig. 43).

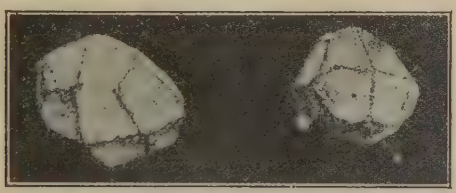

FIG. 43.

Crystals of Pseudo-leucite.

From Spotted Fawn Creek, Yukon Territory, Canada. (*After C. W. Knight*). The crystals are pseudomorphs after leucite, and are composed of the following minerals: orthoclase, scapolite, nepheline, biotite, and a little plagioclase.

The latter mineral is sometimes only represented by a decomposition product. Other minerals such as biotite, augite, hornblende, sphene, etc., are probably inclusions from the original magma in which the leucite

[1] Hussak: *Neues. Jahrb.*, 1887, vol. ii., p. 255, and 1890, vol. i., p. 166; Derby: *Quart. Journ. Geol. Soc.*, vol. xlvii (1891), p 251; J. F. Williams: *Amer. Journ. Sci.*, vol. i. (1895), p. 194; Teall: Geological Structure North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 443; Shand: *Neues. Jahrb.*, xxii., 1906, p. 413; Knight: *Amer. Journ. Sci.*, vol. xxi., 1906, p. 286.

crystals were formed. Derby suggests that the crystals of leucite rich in inclusions which were first formed, were subsequently altered to an aggregate of orthoclase and nepheline by some magmatic change before final consolidation took place.

Melilite (Humboldtilite). Silicate of alumina, iron, lime, magnesia, and soda: $12(CaMg)O$, $2(AlFe)_2O_3$, $9SiO_2$. Tetragonal; occurring in small square tablets

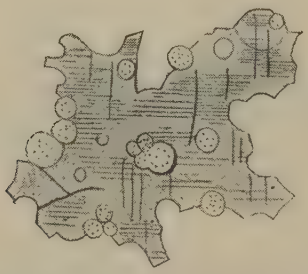

FIG. 44.
Melilite in the lava of Capo di Bove, near Rome.

FIG. 45.
Peg-structure in Melilite, highly magnified.

and prisms, also in irregular grains. Colour, white to yellow. Gelatinizes easily with hydrochloric acid. Sp. G. = 2·90–2·95. Hardness = 5–5·5. Index of refraction, 1·629; double refraction, weak—the same as nepheline—the interference colour in thin section being commonly an indigo-blue.

Under the microscope melilite appears in lath-shaped sections, which are characterized by a striation normal to the long axis (*peg structure*, see Fig. 45).

Occurs as a constituent of certain basalts (melilite-basalt) and nepheline- and leucite-rocks.

Sodalite. Silicate of alumina and soda, + sodium chloride: $3(Na_2O, Al_2O_3, 2SiO_2) + 2\,NaCl$ with $SiO_2 = 37{\cdot}2$, $Al_2O_3 = 31{\cdot}6$, $Na_2O = 25{\cdot}6$, $Cl = 7{\cdot}3$ per cent. less 1·70 for Cl. Regular. Sp. G. = 2·1–2·3. Hardness = 5·5. Index of refraction, 1·484; isotropic. Gelatinizes easily with hydrochloric acid.

Occurs in blue, greenish, or colourless grains in syenites and in volcanic ejectamenta. Under the microscope it presents colourless or faintly blue sections, which remain dark when rotated between crossed nicols. Numerous inclusions.

Haüyne and Nosean.—Isomorphous silicates of alumina, lime, and soda, together with sulphate of soda. The soda end of the isomorphous series with little or no lime is nosean $= 3(Na_2O, Al_2O_3, 2SiO_2) + 2\,Na_2SO_4$, with $SiO_2 = 31{\cdot}7$, $SO_3 = 14{\cdot}1$, $Al_2O_3 = 26{\cdot}9$, and $Na_2O = 27{\cdot}3$. When $Na_2 : Ca = 3 : 2$, the composition of haüyne is $SiO_2 = 32{\cdot}0$, $SO_3 = 14{\cdot}2$, $Al_2O_3 = 27{\cdot}2$, $CaO = 10{\cdot}0$, $Na_2O = 16{\cdot}6$. Regular. Sp. G. = 2·27–2·50. Hardness = 5–5·5. Index of refraction, 1·496; isotropic. Gelatinize easily with hydrochloric acid; on evaporation, needles of gypsum are formed in the case of haüyne, none in the case of nosean. The minerals are very similar in composition and appearance. Haüyne, however, is generally blue, and nosean colourless or yellow. Under the microscope these minerals present square or six-sided sections, which

remain dark when rotated between crossed nicols. The sections are characterized by the presence of numerous minute inclusions aggregated to a marginal or zonal dark band, or accumulated in the centre as a grey shaded patch. In other cases they are arranged

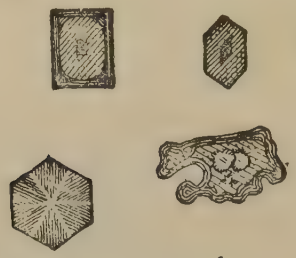

FIG. 46.
Crystals of Haüyne, showing the mode of arrangement of the inclusions.
(After Rosenbusch.)

along axes intersecting in the centre at 60°. (See Fig. 46.) They are essentially volcanic minerals, occurring as sporadic grains in phonolites, andesites and basalt; also in volcanic ejectamenta (Vesuvius, Lake Laach in the Eifel).

AMPHIBOLE GROUP.

The amphiboles are silicates mainly of magnesia, lime and iron; other bases occurring in some varieties are alumina, manganese and soda. They are nearly all monoclinic, only one variety being rhombic (anthophyllite) and one triclinic (cossyrite).

Sp. G. = 2·90–3·55. Hardness = 5–6. Unattacked by acids. Cleavage, parallel to the prism (as in Fig. 48), well-marked. The angle made by the prism

faces is about 124° (see Fig. 47), which constitutes a useful distinction from augite, in which the prism faces intersect at an angle of about 87°.

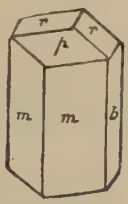

FIG. 47.
Back view of a Crystal of Hornblende.

p. Orthodome. | *m*. Prism.
r. Clinodome. | *b*. Clinopinacoid.

Under the microscope, sections perpendicular to the vertical axis are generally six-sided (being bounded by two clinopinacoidal and four prismatic

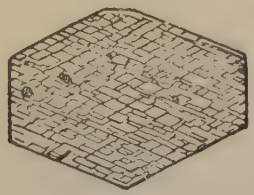

FIG. 48.
Cross-section of Hornblende, showing the prismatic cleavage.

planes), with cleavage-lines intersecting at an angle of 124°. (See Figs. 47 and 48.) They frequently show dual, more rarely multiple, twinning. Index of refraction, 1·622–1·72. The double refraction is

high, even thin sections giving chromatic polarization. The coloured varieties are strongly pleochroic (distinction from augite).

By alteration processes (weathering, metamorphism, etc.) the amphiboles give rise to chlorite, serpentine and calcite.

1. Monoclinic Amphiboles.

a. Brown and Green Amphiboles.

Common Hornblende. Monoclinic. Metasilicate of iron, alumina, lime and magnesia, with smaller amounts of soda and potash, lime forming about one quarter of all the bases. The so-called "basaltic hornblende" contains a larger proportion of ferric iron and titanium than common hornblende. Colour, black by reflected light; brown or green by transmitted light. Pleochroism, strong in brown and yellow, or green and yellow tints. Index of refraction, 1·642. Double refraction, high. Extinction angle for the brown variety, 10° to 15°; for the green, 12° to 20°.

Occurs in hornblende-granites, syenites and monzonites (brown and green varieties poor in alumina); diorites and gabbros (mainly the green aluminous variety); phonolites, trachytes (usually a green soda-bearing variety), and andesites (brown variety); and as an accessory constituent of basalts. The crystals are among the first-formed constituents, and have often suffered subsequent corrosion in the still molten magma, being then surrounded by a dark-coloured border.

b. Green Amphiboles.

Actinolite. Monoclinic. Silicate of iron, magnesia and lime: $CaO, 3(MgFe)O, 4SiO_2$. Colour, grass-green. Pleochroism, in green tints, not very strong. Maximum extinction-angle = 15° to 18°. Index of refraction, 1·626. Double refraction, higher than that of common hornblende, excepting basaltic hornblende, which has

FIG. 49.

Crystals of Hornblende, under the microscope, showing the predominance of the prism faces over those of the pinacoids, and the prismatic cleavage.

(*After Teall.*)

a much higher birefringence than either. Occurs in long prisms and needles, or in ribbon-like blades and fibres, as a constituent of amphibolite and hornblende-schist. **Smaragdite, nephrite** and **uralite** are fibrous green hornblendes allied to actinolite, generally secondary after pyroxene. Such paramorphic hornblende occurs in gabbros, diabases and epidiorites.

Pilite is a similar substance produced by the alteration of olivine.

c. White Amphiboles.

Tremolite. Monoclinic. Silicate of magnesia and lime: $CaO, 3MgO, 4SiO_2$. Colourless. Maximum extinction = 15° to 17°. Index of refraction, 1·621. Double refraction, the same as actinolite. Occurs in lamellar and bladed aggregates as a constituent of metamorphic limestones (cipollino). **Asbestos** is a fibrous variety of tremolite; although *commercial asbestos* chiefly consists of chrysotile (serpentine).

d. Soda Amphiboles.

Arfvedsonite. Monoclinic. Silicate of soda and iron: $(Na_2Fe)O, SiO_2$.

Resembles common green hornblende, but is of a more bluish hue. Maximum extinction-angle varies from 10° to 14° = (80° to 76°). Occurs in association with the soda-minerals — elæolite, nepheline and leucite—in elæolite-syenite, phonolite, etc.

Barkevikite is a similar hornblende, but brown in colour and containing titanic acid, and with a positive extinction-angle of from 10° to 14°. Index of refraction, 1·704. Double refraction, high, but less than actinolite. **Katophorite** occupies an intermediate position between arfvedsonite and barkevikite.

Glaucophane. Monoclinic. Silicate of alumina and soda—$Na_2O, Al_2O_3, 4SiO_2$. Colour, blue. Pleochroism striking, in blue and reddish violet tints. (γ = blue, β = reddish violet, α = colourless to yellow), (See Fig. 57.) Maximum extinction-angle—3° to 11°. Occurs in prisms and blades in schistose rocks

(Anglesey, Isle of Syra, Japan). **Gastaldite** is a variety.

Riebeckite.[1] Monoclinic. Silicate of soda and iron : Na_2O, Fe_2O_3, $4SiO_2$. Colour, deep blue. Pleochroism in blue and green tints, (γ = green, β = blue, α = deep blue and nearly coincident with the vertical axis). (See Fig. 57.) Maximum extinction—2° to 7° (= 88° to 83°). Riebeckite occupies a position among the amphiboles equivalent to that of ægirine and acmite among the pyroxenes. Occurs in certain microgranites and trachytes (Socotra, Mynydd Mawr in Wales, Ailsa Craig and Eildon Hills in Scotland). **Crocidolite** is a similar variety.

2. Rhombic Amphibole.

Anthophyllite. Rhombic. Silicate of magnesia and iron : (MgFe)O, SiO_2. Colourless. Extinction, straight. Index of refraction, 1·633. Double refraction, high, but less than actinolite. Occurs in bladed forms in amphibolites ; also in fibrous zones around the olivines of some gabbros.

3. Triclinic Amphibole.

Cossyrite. Triclinic. Silicate of alumina, iron and soda. Under the microscope this mineral appears in prisms of a deep reddish-brown colour, only transmitting light in very thin sections.

It is only known to occur in the rhyolites of Pantelleria (pantellerites).

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[1] Discovered by Sauer (1888) in granite collected by Dr. Riebeck in Socotra.

PYROXENE GROUP.

The pyroxenes are silicates of iron, magnesia and lime: the bases alumina, manganese, soda and lithia, also occur in some varieties. They are unattacked by acids. Sp. G. = 3–3·5. Hardness = 5–6. Cleavage parallel to the prism (angle = 87°), rather imperfect.

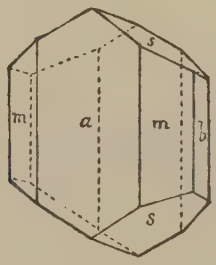


FIG. 50.
Crystal of Augite.
a. Orthopinacoid.
b. Clinopinacoid.
m. Prism.
s. Pyramid.
(*After Rosenbusch.*)

The smaller angle between the prism-faces and the inferior degree of cleavage constitute the main points of distinction from hornblende. Under the microscope sections perpendicular to the vertical axis are octagonal, being bounded by the faces of the prism and of both pinacoids. With regard to maximum extinction-angles in the monoclinic pyroxenes, these are high (38° to 54°) in the diopside-augite series; 6° to 38° in the ægirine-augite series, and 0° to 6° in the acmite-ægirine series. In the rhombic pyroxenes

the extinction is of course straight. Index of refraction, 1·668 (enstatite) to 1·799 (acmite). Double refraction, high in the monoclinic augites, but moderate in the rhombic pyroxenes.

1. Rhombic Pyroxenes.

Meta-silicates of iron and magnesia—$(MgFe)O, SiO_2$. According to the percentage of iron they contain, the following varieties may be distinguished :—

Enstatite, with less than 5% of FeO.
Bronzite, 5 – 14% of FeO.
Hypersthene, above 14% of FeO.
Amblystegite, up to 31% of FeO.

FIG. 51.
Longitudinal section of Enstatite.

For practical purposes enstatite represents the meta-silicate of magnesia, or MgO, SiO_2, with $SiO_2 = 60$ and $MgO = 40$ per cent. In the same way hypersthene may be regarded as $3MgO, FeO, 4SiO_2$, with $SiO_2 = 55{\cdot}5$, $MgO = 27{\cdot}7$ and $FeO = 16{\cdot}8$ per cent.; while amblystegite would have the formula $MgO, FeO, 2SiO_2$, in which $SiO_2 = 51{\cdot}8$, $MgO = 17{\cdot}2$ and $FeO =$

31·0 per cent. Intensity of colour and pleochroism increase with the percentage of iron, enstatite being colourless and non-pleochroic in thin section, bronzite slightly coloured and pleochroic, and hypersthene and amblystegite strongly so.

The rhombic pyroxenes are characterized by the possession of a fairly perfect pinacoidal cleavage, in addition to the prismatic cleavage common to all pyroxenes. In some varieties the pinacoidal cleavage surfaces have a sub-metallic (bronzy or coppery) lustre. This phenomenon is caused by reflection from the surfaces of innumerable parallel rods and flakes of

FIG. 52.
Cross-section of Enstatite.

foreign matter intercalated along these planes, and said to be of secondary origin.

Between crossed nicols the rhombic pyroxenes extinguish, of course, straight. Index of refraction, 1·66 to 1·70. The double refraction is moderate; in enstatite it is the same as that of quartz, but hypersthene has a higher birefringence. The pleochroism of hypersthene is as follows: α = sea-green, β = salmon-red, γ = reddish-yellow.

They occur in various igneous rocks: diorites, monzonites, norites, dolerites, porphyrites, andesites

and some peridotites, and pass by alteration into a fibrous serpentinous substance known as **bastite**.

2. Monoclinic Pyroxenes.

a. Brown Pyroxene.

Common Augite. Silicate of alumina, lime, magnesia and iron. It may be regarded as made up of m molecules of diopside, CaO, $(MgFe)O$, $2SiO_2$

FIG. 53.
Longitudinal section of Augite.

FIG. 54.
Cross-section of Augite.

$+n$ molecules of Tschermak's silicate $(MgFe)O$, $(AlFe)_2O_3$, SiO_2. There is usually a small quantity of soda present, and when the percentage of Na_2O exceeds 2·5 the mineral is termed ægirine-augite, the colour approximating to that of ægirine. Sp. G. = 3·30–3·50. Hardness = 5–6.

This mineral is black by reflected light. In thin section it is colourless or of a pale-green to pale-brown colour, sometimes with a violet tinge, especially

FIG. 55.
Crystal of Augite showing hour-glass structure.

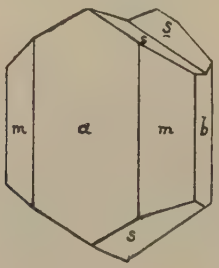


FIG. 56.
Crystals of Augite twinned on the Orthopinacoid
a. Orthopinacoid.
b. Clinopinacoid.
m. Prism.
s. Pyramid.
(*After Rosenbusch.*)

when the mineral contains titanium. Pleochroism, faint or absent. Index of refraction, 1·70 to 1·72. High double refraction, but slightly less than actinolite.

Extinction angle, in sections parallel to the vertical axis, reaches a maximum of 54°, constituting thus a distinction from hornblende. Slight variations in the extinction angle in different peripheral layers often produce in the crystals a zonal structure, which occasionally assumes the form of an hour-glass. (See Fig. 55.) The cleavage is less perfect than in hornblende, the cracks being irregular, thick and branching in thin section. Dual and even multiple twinning (parallel to the orthopinacoid), not uncommon. (See Fig. 56.)

Augite passes readily into chlorite by the ordinary process of weathering: dynamic metamorphism converts it into green hornblende (uralite, actinolite, etc.).

Loose crystals of black opaque augite occur among the material ejected from volcanoes (lapilli, cinders, ash, etc.). It is a very common constituent both of plutonic and volcanic rocks, especially of the more basic varieties: gabbro, dolerite, andesite, basalt, etc.

Diallage is a laminated variety of augite, usually of a greenish colour, occurring in gabbro. The lamination is parallel to the orthopinacoid; it appears in thin section as a fine lineation, which constitutes the chief diagnostic character of the mineral. The faces of this lamination or pseudo-cleavage, are characterized by a pearly or sub-metallic lustre, due to the presence of minute included plates and rods. Thin pieces, flaked off in this direction and examined in convergent polarized light, present the oblique emergence of an optic axis (distinction from the rhombic

pyroxenes). **Salite** is a similar mineral in which the inclusions are parallel to the basal plane.

b. Green and White Pyroxenes.

Diopside, Malacolite, Coccolite, Omphacite. Meta-silicates of lime, magnesia and iron: CaO, (MgFe)O, $2SiO_2$. Pure diopside may be regarded as CaO, (MgFe)O, $2SiO^2$ in which the ratio between MgO and FeO is variable, MgO being usually in excess. Sp. G. = 3·3. Index of refraction, 1·68; double refraction, high, but slightly less than common augite.

In colour these non-aluminous monoclinic pyroxenes vary from a very pale-green (malacolite) to a bright grass-green (omphacite, chrome-diopside). Malacolite occurs in grains and prisms in certain diorites, epidiorites and metamorphic schists. Bright green pyroxene (omphacite, chrome-diopside) occurs in some peridotites, also in eclogite, pyroxene-granulite, etc.; coccolite occurs in metamorphic limestones.

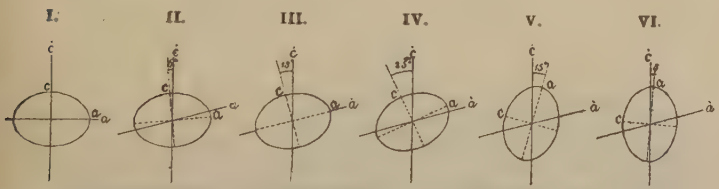
Under the microscope malacolite gives colourless sections, which on account of their fairly high index of refraction may easily be mistaken for epidote. It is distinguished from this mineral, however, by an oblique extinction in lath-shaped sections, and by the absence of pleochroism.

Wollastonite. Meta-silicate of lime: CaO, SiO_2, with SiO_2 = 51·72, and CaO = 48·28 per cent. Monoclinic. Sp. G. = 2·78–2·9. Hardness = 4·5–5. Perfect cleavage parallel to the basal plane and to the orthopinacoid. Colourless, with pearly lustre. Occurs in columnar crystals with fibrous structure, and in

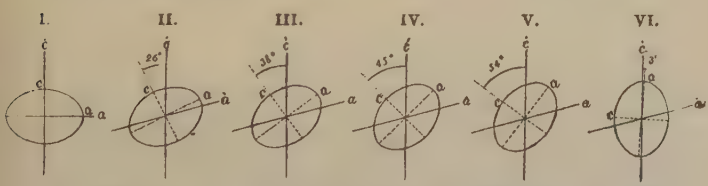
fibres in metamorphic limestones and crystalline schists. Easily decomposed by hot hydrochloric acid; and the solution, on the addition of dilute sulphuric acid, yields crystals of gypsum.

c. Soda-pyroxene.

Acmite and **Ægirine**, corresponding to arfvedsonite, glaucophane, etc., among the amphiboles. Ideally pure acmite is a meta-silicate of sodium and ferric iron, and corresponds to the formula Na_2O,



I. Anthophyllite. II. Glaucophane. III. Tremolite, brown hornblende, etc. IV. Green hornblende. V. Blue amphibole (Silver Cliff). VI. Riebeckite.



I. Enstatite, etc. II. Spodumene. III. Diopside, etc. IV. and V. Augite. VI. Ægirine.

FIG. 57.

$Fe_2O_3, 4SiO_2$; with $SiO_2 = 52{\cdot}0$, $Fe_2O_3 = 34{\cdot}6$ and $Na_2O = 13{\cdot}4$; but usually the bases CaO, MgO, and Al_2O_3 are present in small quantities and the mineral is termed ægirine. When these are increased and

the soda diminished, the ægirine passes through ægirine-augite into common augite, so that acmite, ægirine, ægirine-augite, and augite are members of an isomorphous series. Ægirine is found in certain members of the alkali series of plutonic and volcanic rocks, as for instance in syenites, nepheline-syenites and in phonolites.

The foregoing diagram (after Iddings) shows the relation existing between the morphological axes and the axes of elasticity in the principal amphiboles and pyroxenes. The angle given is that of extinction.

OLIVINE GROUP.

Olivine. Ortho-silicate of iron and magnesia: $2(MgFe)O, SiO_2$. Occasionally the bases CaO, MnO and ZnO are represented in minerals developed in metamorphic limestones, while the iron-magnesium compound or common olivine occurs most commonly in the igneous rocks. The following members of the isomorphous series deserve mention.

Forsterite, $2MgO, SiO_2$; with $SiO_2 = 42{\cdot}9$ and $MgO = 57{\cdot}1$.

Fayalite, $2FeO, SiO_2$; with $SiO_2 = 29{\cdot}4$ and $FeO = 70{\cdot}6$.

Tephroite, $2MnO, SiO_2$.

Monticellite, CaO, MgO, SiO_2.

Titanolivine, with 5–6% of titanic acid.

Olivine, $2(MgFe)O, SiO_2$; with MgO varying from 31–52%, and FeO from 5–30%.

Rhombic. Occurs in tabular or prismatic forms, made up of pinacoids and domes, or in irregular grains. Sp. G. = 3·2–3·5. Hardness = 6·5–7. Gela-

tinizes with hydrochloric acid. Colour, black, olive-green, or yellow. Pinacoidal cleavage, imperfect. Under the microscope olivine presents colourless sections, sometimes bounded by crystallographic contours, oftener by irregular and indented outlines, due to corrosion. (See Fig. 58.) Its index of refraction is high (1·678), the outlines being strongly marked and the surface of the sections having a roughened appearance. The double refraction is also

FIG. 58.
Corroded crystal of Olivine.

high, the sections polarizing in bright colours. Unaltered olivine is, on account of its optic properties, liable to confusion with diopside, but the fact that the cleavage is pinacoidal in the former and prismatic in the latter is a useful distinction. Straight extinction in all principal sections. Inter-penetration twins are not infrequent in basalt. (See Fig. 59.) They are best seen between crossed nicols on account of the difference in extinction shown by the two individuals.

Olivine is very prone to decomposition; it alters

readily into serpentinous products (antigorite, iddingsite), also into calcite or dolomite, limonite, and more rarely into hornblende (pilite, anthophyllite).

FIG. 59.
Twin-crystal of Olivine.

Olivine occurs only in basic and ultrabasic rocks: in gabbros, dolerites, basalts, limburgites, picrites, peridotites, etc. The peridotites are mainly composed of this mineral. Olivine alters readily into fibrous aggregates of serpentine; the alteration proceeding along cracks, and being often accompanied by a separation of iron-ores (magnetite, limonite, etc.).

MICA GROUP.

The rock-forming micas may be divided for all practical purposes into white and black micas.

In white mica (muscovite), there is usually a considerable divergence of the optic axes; while the dark mica (biotite) is, in most cases, practically uniaxial, *i.e.*, the two optic axes are nearly coincident. There are, however, certain rare varieties of dark mica that have a large optic axial angle. All micas are monoclinic, but with pseudo-hexagonal symmetry (see Fig. 60); and a very perfect basal cleavage is

characteristic for the group. The elasticity of the laminæ distinguishes mica from other minerals (talc, chlorite, etc.) possessing a similar cleavage.

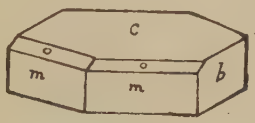


FIG. 60.

Crystal of Mica.
c. Basal Plane.
o. Pyramid.
m. Prism.
b. Clinopinacoid.
(*After Rosenbusch.*)

WHITE MICAS.

Muscovite, or Potash-mica. Hydrated orthosilicate of alumina and potash: K_2O, $3Al_2O_3$, $6SiO_2$, $2H_2O$ (Tschermak), $= SiO_2$, 45·2; Al_2O_3, 38·5; K_2O, 11·8; H_2O, 4·5. Not attacked by hydrochloric acid. Sp. G. = 2·76–3·1 Hardness 2–3. Index of refraction, 1·592. Double refraction, very high, thin sections giving brilliant chromatic polarization between crossed nicols. Sections parallel to the basal plane, however, exhibit a low interference-colour, usually grey.

Occurs in granite and gneiss, in plates, leaves, scales and fibres, possessing a silvery white colour and bright lustre. Fragments of muscovite are frequently present in sandstones and shales, and by their parallel arrangement impart to these rocks a fissile character. Under the name of **sericite** a silvery white or pale-green variety occurs as a frequent secondary con-

stituent of the metamorphic schists. There is no doubt that in many cases it results from the alteration of the felspar. Its thin laminæ wrap round the lenticular masses of quartz and felspar, and play an important part in determining the schistosity of these rocks.

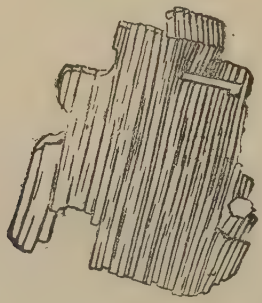


FIG. 61.
Section of Mica showing the cleavage.

Other white micas are **paragonite**, a hydrated silicate of alumina, and soda (Na_2O, $3Al_2O_3$, $6SiO_2$, $2H_2O$) occurring in schists; **margarite**, a hydrated silicate of alumina and lime, in schists; and **lepidolite** and **zinnwaldite**, hydrated silicates of alumina, potash, soda and lithia, in pegmatites and greisens. Under the microscope the white micas give lath-shaped sections, presenting well-marked cleavage-lines, often bent. They also occur in streaky and ribbon-like bands.

Black or Ferro-Magnesian Micas.

Biotite, a hydrated silicate of alumina, iron, magnesia and potash $(HK)_2O,2(Mg,Fe)O,(Al,Fe)_2O_3$,

$3SiO_2$. Attacked by hot hydrochloric acid. Sp. G. = 2·8–3·2. Hardness = 2·5–3. Index of refraction, 1·56. Double refraction, very high, the colours being bright except in sections parallel to the basal cleavage, which remain dark when rotated between crossed nicols.

Occurs as a constituent of some granites, syenites, diorites, lamprophyres, trachytes and andesites, also, as an accessory in some basalts. Loose crystals of a reddish brown biotite (rubellan) are found embedded in volcanic ash.

Under the microscope this mineral appears in plates, scales, and lath-shaped sections, the latter showing intense pleochroism (pale yellow to chestnut brown an black). The principal absorption takes place when the long axis of the lamella, or the trace of the cleavage, is parallel to the short diagonal of the polarizing nicol, thus distinguishing it from tourmaline, which is equally strongly absorptive, but in a direction at right angles to this. Inclusions are frequent: tourmaline, zircon, orthite, sphene, and apatite, the last four of which are often surrounded by pleochroic borders. Intergrowths with hornblende and pyroxene are common. Alters easily to chlorite, the alteration being marked by the gradual assumption of a green colour. **Lepidomelane** is a variety of biotite, rich in ferric iron.

Phlogopite is a magnesian mica, rich in potassium, and with variable amounts of fluorine and hydrogen. It has little or no iron. Formula = $HK(MgF)_3Mg_3Al(SiO_4)_3$.

SCAPOLITE GROUP.

Scapolite. Silicate of alumina, lime and soda, + sodium chloride. The scapolite group, like the lime-soda plagioclase group, may be regarded as isomorphous mixtures of two molecules, viz., the Meionite (Me) molecule ($4CaO, 3Al_2O_3, 6SiO_2$), with $SiO_2 = 40{\cdot}5$, $Al_2O_3 = 34{\cdot}4$, and $CaO = 25{\cdot}1$, and the Marialite (Ma) molecule ($Na_4Al_3Si_9O_{24}Cl$); with $SiO_2 = 63{\cdot}9$, $Al_2O_3 = 18{\cdot}1$, $Na_2O = 14{\cdot}7$ and $Cl = 4{\cdot}20$ (oxygen for chlorine to be deducted). *Wernerite* includes scapolites with Me : Ma ranging from 3 : 1 to 1 : 1, *Mizzonite* those with Me : Ma ranging from 1 : 2 to 1 : 3. *Couseranite* and *Dipyre* are varieties of mizzonite. Tetragonal. Sp. G. = 2·6 – 2·8. Hardness = 5–5·5. Index of refraction, 1·55–1·78. Colourless. Of infrequent occurrence in igneous rocks; oftener in gneisses and crystalline schists and in contact-altered limestones, calc-silicate rocks, etc.[1] Under the microscope, occurs in irregular colourless grains, possessing a well-defined cleavage. Double refraction high, between actinolite and orthite.

GARNET GROUP.

The garnets are silicates of alumina, iron, manganese, chromium, lime and magnesia, having the general formula $3MO, R_2O_3, 3SiO_2$.[2] According to

[1] Flett : *Summary of Prog. Geol. Surv.*, 1906, p. 116.

[2] M standing for metals like calcium, magnesium, etc., forming protoxides ; R for those like aluminium and chromium, forming sesquioxides.

the variation of MO and R_2O_3, the following varieties may be distinguished.[1]

Name.	Constituent Bases.		Colour.	Specific Gravity.	Index of Refraction.
Grossularia	CaO	Al_2O_3	pale green	3.4–3.6	1.747
Almandine	FeO	Al_2O_3	claret	3.5–4.3	1.807
Pyrope	FeO, MgO, CaO	Al_2O_3, Cr_2O_3	blood red	3.7–3.8	1.745
Melanite	CaO	Fe_2O_3	blackish brown	3.6–4.3	1.856
Spessartine	MnO	Al_2O_3	light reddish	3.7–4.3	1.810
Uvarovite	CaO	Cr_2O_3	green	3.4–3.5	1.838

Other garnets consist of mixtures of these molecules.

The garnets are insoluble in acids. They have a hardness of 6·5–7.5, irregular fracture and resinous lustre. They crystallize in the Regular System, the most common form being the rhombic dodecahedron, the edges of which are sometimes truncated by icositetrahedral faces.

Under the microscope garnet appears in irregular, or in 4- and 6-sided, grains which are colourless or pink. Rotated between crossed nicols they remain dark, the mineral being isotropic; in exceptional cases there is a feeble transmission of light, such garnets being optically anomalous. The sections are traversed by irregularly branching cracks, produced by an imperfect cleavage parallel to the rhombic dodecahedron. The index of refraction is fairly high (1·747 to 1·858), giving the grains bold contours. Alteration products are chlorite, hornblende, serpentine.

As an accessory constituent of igneous rocks garnet is common enough, occurring in granites, alkali-gabbros

[1] Lévy and Lacroix.

(borolanite), microgranites, aplites, and trachytic and andesitic rocks; it is found also in the gneisses and crystalline schists, and in the sands produced by the disintegration of these and similar rocks. It is constant in its occurrence in some of the peridotites and allied rocks: eclogite, pyroxene-granulite, etc.

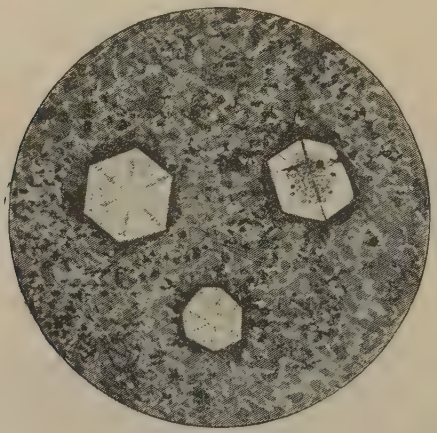


FIG. 62.
Section of a rock containing Garnets. (*After Renard.*)

TOURMALINE GROUP.

Tourmaline. A complex hydrated silicate and borate of alumina, magnesia and soda, with iron, manganese, lime and small quantities of potash, lithia and fluorine. The tourmalines may, according to their constituent bases, be classified as alkali-tourmalines, iron-tourmalines, magnesium-tourmalines, etc. They all contain about 10 per cent. of boric acid, and from $3\frac{1}{2}$ to 4 per cent. of water.

Rhombohedral, occurring in triangular prisms with rhombohedral termination. The prisms show a vertical striation. Often in fibrous veins and stellate aggregations. Sp. G. = 2·94–3·24. Hardness = 7–7·5. Index of refraction, 1·635. Unattacked by acids. Colour, usually black, but also blue, green, pink, and more rarely white or colourless. Vitreous lustre. Under the microscope, the lath-shaped, prismatic

FIG. 63.

Crystals of Tourmaline, from the Bagshot sands at Hampstead, under the microscope. (*After Teall.*)

sections extinguish straight. Marked pleochroism in violet, blue, green and brown colours; the deeper colour always appearing when the long axis of the section is perpendicular to the short diagonal of the polarizing nicol (distinction from biotite). Double refraction, high; that of a chrome-bearing variety, very high, between muscovite and talc. The variety

schorl occurs in microgranites (*e.g.*, the elvans of Devon and Cornwall), in the marginal portion of granites (*e.g.*, luxulyanite[1]), and in the altered rock in contact with granite (schorl-rock). It also occurs in pegmatite veins. Prisms of tourmaline are common in clays and sands.[2] (See Fig. 63.)

EPIDOTE GROUP

Epidote. Silicate of lime, alumina and iron: H_2O, $4CaO$, $3(AlFe_2)O_3$, $6SiO_2$. Monoclinic, in crystals elongated parallel to the orthodiagonal axis. Lath-shaped sections therefore give straight extinction between crossed nicols. Sp. G. = 3·39. Hardness = 6 – 7. Index of refraction, 1·73 – 1·75. Unattacked by hydrochloric acid. Colour, yellowish-green. Perfect cleavage parallel to the basal plane. Epidote occurs as a joint alteration-product of the felspathic and the ferro-magnesian minerals, in gabbros, diorites, epidiorites and hornblendic and chloritic schists. It is also found veining these rocks, or associated with other secondary minerals in the amygdales of old lavas. Under the microscope it appears in small colourless to yellow grains or prisms, showing strong relief due to a high index of refraction. When coloured it is faintly pleochroic. High double refraction, slightly higher than that of olivine.

Piedmontite or **Withamite** is a red, markedly pleochroic variety of epidote, in which manganese replaces a portion of the iron. It occurs in a porphyrite dyke at the Meeting of the Three Waters,

[1] Bonney: *Min. Mag.*, 1877, p. 215.
[2] Dick: *Nature*, vol. xxxvi., p. 91.

Glencoe, in Scotland; in the famous *Porfido rosso antico* of Egypt, and in certain Japanese mica-schists. (Piedmontite-schist.) **Orthite** or **Allanite** is a brown to black variety of epidote containing cerium and yttrium metals.

Zoisite. Silicate of lime and alumina: H_2O, $4CaO$, $3Al_2O_3$, $6SiO_2$. Rhombic, occurring usually in columnar aggregates of a whitish-grey colour. Sp. G. = 3·25–3·36. Hardness = 6. Index of refraction, 1·696–1·7. Unattacked by hydrochloric acid. Under the microscope it presents colourless prisms and granules, resembling epidote, but distinguishable from that mineral by its lower double refraction, which is slightly higher than nepheline but less than orthoclase. Occurs in association with epidote in altered basic igneous rocks and metamorphic schists.

PHOSPHATE AND FLUORIDE GROUP.

The apatites are phosphates of lime + chloride or fluoride of lime: **Fluor-apatite,** $3(3CaO, P_2O_5) + CaF_2$; with $P_2O_5 = 42·3$, $CaO = 55·5$, $F = 3·8$ per cent. less 1·6 O for F. **Chlor-apatite,** $3(3CaO\ P_2O_5) + CaCl_2$; with $P_2O_5 = 41·0$, $CaO = 53·8$, $Cl = 6·8$ per cent. less 1·6 O for Cl. There are also intermediate varieties containing both fluorine and chlorine. Hexagonal. Sp. G. = 3·16–3·22. Hardness = 5. Imperfect cleavage parallel to basal plane and prism, the latter scarcely noticeable under the microscope. When fresh, colourless and glassy; altered varieties are dull green and red. Soluble in acids without gelatinization: the nitric acid solution gives a yellow

precipitate with ammonium molybdate (distinction from nepheline).

Apatite occurs in long hexagonal prisms and needles; also in short prisms. It is one of the commonest accessory minerals, being found in most igneous rocks. It is especially abundant in the gabbros, dolerites and basalts. It is also one of the earliest-formed constituents; for its needles are usually found penetrating all other minerals. Under the microscope it is colourless, and presents six-sided cross sections and elongated lath-shaped longitudinal sections. The former remain dark when rotated between crossed nicols, the latter extinguish straight. Double refraction, weak, the polarization colour being grey. Index of refraction, rather high (1·637). There is often a central core of inclusions; and in such cases there is usually a slight absorption of light when the long axis of the section is parallel to the short diagonal of the nicol. Apatite may be easily mistaken for nepheline. It is distinguished from this mineral by the chemical reactions mentioned above, by the index of refraction, and by the fact that apatite occurs in rocks in slender, needle-like prisms, nepheline on the other hand, in shorter and thicker prisms. Of the two varieties of apatite, chlor-apatite occurs more frequently in basic rocks, and fluor-apatite more frequently in acid rocks.

Xenotime (phosphate of yttrium, and **Monazite** (phosphate of cerium and lanthanum) are rare minerals, occurring in sands and probably derived from igneous rocks. Prof. Derby has described them in the muscovite-granites of Brazil. Xenotime occurs in pyramidal crystals of the Tetragonal System, which

are transparent, yellow, or colourless, with highly polished faces. By alteration it becomes opaque. Refraction and double refraction, very high. Monazite crystallizes in the Monoclinic System. Index of refraction, 1·811. Double refraction, very high.

Fluorspar. Fluoride of calcium: CaF_2, with Ca = 51·1 and F = 48·9. Regular. Sp. G. = 3·18 – 3·19. Hardness = 4. Decomposed by sulphuric acid. Octahedral cleavage, perfect. Index of refraction, 1·434. Isotropic. In thin section, colourless to violet or blue. Occurs in small quantities in granites, syenites, and especially in nepheline-bearing rocks.

IRON-ORE GROUP.

The iron-ores that occur as common accessory constituents of rocks are magnetite or magnetic iron-ore, ilmenite or titaniferous iron-ore and pyrites.

Magnetite. Magnetic oxide of iron: FeO, Fe_2O_3, with FeO = 31·0, and Fe_2O_3 = 69·0 per cent. The

FIG. 64.
Crystals of Magnetite.
(*After Rosenbusch.*)

ferrous iron may be partially replaced by magnesium and by manganese. Regular. Sp. G. = 4·9 – 5·2. Hardness = 5·5 – 6·5.

One of the commonest accessory constituents of igneous rocks, occurring in black octahedral grains, skeleton-crystals, and minute particles. Under the microscope it is perfectly opaque, even in the thinnest sections. In reflected light it has a bluish-black metallic lustre (distinction from pyrites and ilmenite). (See Fig. 64.) The amount of magnetite present in the igneous rocks varies. It sometimes increases locally to a considerable extent, as in the dark patches of granitic rocks. Törnebohm and Vogt have shown that, in certain differentiations of basic igneous rocks, a gradual increase in the percentage of iron-ore may be observed up to 90 per cent.

Ilmenite. Titaniferous oxide of iron: $(TiFe)_2O_3$. Rhombohedral. Sp. G. = 4·5 – 5·2. Hardness = 5 – 6.

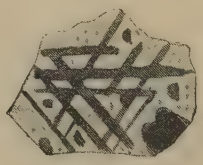


FIG. 65.
Section of Ilmenite.

Infusible. Attacked with difficulty by acids. Black and opaque in thin section. Occurs in hexagonal sections, but oftener in irregular grains, and then not easy to distinguish from magnetite. It may be distinguished from that mineral, however, by the fact that it is very liable to alteration into a white opaque substance, known as *leucoxene* (a variety of sphene), by which it is almost invariably accompanied. The

alteration takes place along three systems of lamellæ intersecting at 60°, thus indicating the rhombohedral character of the mineral. Ilmenite occurs in basic igneous rocks, especially in gabbro, dolerite, etc.

Pyrites. Sulphide of iron: FeS_2, with Fe = 46·6 and S = 53·4 per cent. Regular; in cubes and pentagonal dodecahedra. Sp. G. = 4·9 – 5·2. Occurs abundantly disseminated in minute yellow specks and grains in both igneous and sedimentary rocks.

Under the microscope it is opaque; in reflected light, however, its brassy yellow colour at once characterizes it.

SPINEL GROUP.

The spinel group consists of a series of minerals crystallizing in the Regular System, and composed of a double molecule formed by the union of a sesquioxide (Fe_2O_3, Al_2O_3, Cr_2O_3) with a protoxide (FeO, MgO, MnO, ZnO, CrO).

The commonest combinations occurring in rocks are the following :—

	Formula.	Colour.	Specific Gravity.	Hardness.	Index of Refraction
Spinel	MgO, Al_2O_3	red	3.5-4.1	8	1.715
Pleonaste	$(MgFe)O, (AlFe)_2O_3$	dark green	3.6	8	
Hercynite	(FeO, Al_2O_3)	,,	3.9	7.5-8	1.749
Picotite	$(FeMg)O, (CrFeAl)_2O_3$	yellowish brown	4.0	8	
Chromite	FeO, Cr_2O_3	dark brown to opaque	4.5	5.5	2.096
Magnetite	FeO, Fe_2O_3	black and opaque	4.9-5.2	5.5-6.5	

Spinel, MgO, 28.3, and Al_2O_3, 71.7 per cent.
Hercynite, FeO, 41.4 and Al_2O_3, 58.6 per cent.
Chromite, FeO, 32, and Cr_2O_3, 68 per cent.
Magnetite, FeO, 31.0, and Fe_2O_3, 69.0 per cent.

The spinels are abundant in igneous and metamorphic rocks, occurring in small grains and octahedral crystals. Under the microscope they are isotropic. The dark-coloured spinels (pleonaste, hercynite, picotite and chromite) occur frequently in peridotites and serpentines. Magnetite has already been described with the iron-ores. The spinels can be distinguished from the garnets by differences in specific gravity and chemical composition.

ZIRCON GROUP.

Zircon. A double oxide of silicon and zirconium: ZrO_2, SiO_2, with $SiO_2 = 32{\cdot}8$ and $ZrO_2 = 67{\cdot}2$ per cent. Tetragonal; occurring in small prisms terminated at both ends by pyramids. Colour, red and brown.

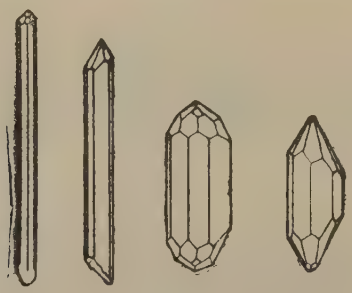


FIG. 66.
Crystals of Zircon. (*After Rosenbusch.*)

Infusible; unattacked by acids, except in fine powder with concentrated sulphuric acid. Sp.G. = 4·1–4·7. Hardness = 7·5. Index of refraction, 1·952. In thin sections zircon occurs in small, colourless grains, with

well-marked contours. Between crossed nicols the polarization colours are brilliant pinks and greens, the double refraction being very high (between talc and sphene).

Zircon has a wide distribution in eruptive (both plutonic and volcanic) and metamorphic rocks. It occurs frequently as an inclusion in black mica, in which case the grains are surrounded by a pleochroic zone. Being undecomposable it is found in the sands derived from granitic and gneissose rocks, and also in the sandstones and quartzites produced by their consolidation.[1]

Eudialyte is a hexagonal mineral allied to zircon. Chemical composition, $2Na_2O$, 3(CaFe)O, ZrO_2, $7SiO_2$. Specific gravity, 2·91–3.0. Index of refraction, 1·613; double refraction, low. It occurs in nepheline-syenites and related pegmatites in the Christiania district of Norway, Kangerdluarsuk in Greenland, the Kola Peninsula of Finland, and at Magnet Cove, Arkansas. **Eucolite** is a variety of the same mineral.

TITANIC ACID GROUP.

Sphene or **titanite.** Silicate and titanate of lime: CaO, SiO_2, TiO_2; with $SiO_2 = 30·6$, $TiO_2 = 40·8$, and $CaO = 28·6$ per cent. Monoclinic. In flat cuneate crystals of a greenish yellow to blackish-brown colour. Sp. G. = 3·3–3·7 Hardness = 5–5·5. Index of refraction, 1·93. Unattacked by hydrochloric acid. Under the microscope sphene appears in irregular, strongly

[1] A. Dick: On zircons and other minerals contained in sand *Nature*, vol. xxxvi., p. 91.

contoured grains, which are occasionally wedge-shaped. Its colour, in thin section, is reddish-yellow. Pleochroism feeble. Double refraction, very high (between zircon and calcite), but not producing brilliant chromatic polarization, the colour effect between crossed nicols being an indefinite brownish grey of a high order. The white opaque substance surrounding ilmenite, and resulting from its alteration, is a variety of sphene, known as **leucoxene**.

Sphene occurs in granites, syenites and crystalline schists; leucoxene in gabbros, diabases, epidiorites and hornblende and chlorite schists.

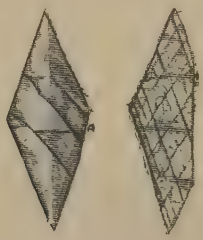


FIG. 67.
Crystals of Sphene.

Perovskite. Titanate of calcium: CaO, TiO_2; with $CaO = 41{\cdot}1$ and $TiO_2 = 58{\cdot}9$ per cent. Regular: in octahedra modified by the dodecahedron and cube. Also in modified cubes. Cleavage, fairly perfect parallel to the cube. Sp. G. = 4·02–4·04. Hardness = 5·5. Index of refraction, high (2·38). Isotropic, but with occasional anomalous double refraction. Colour in transmitted light, grey to violet grey, brown to reddish. Occurs in basic igneous rocks usually in

association with nepheline, leucite, or melilite, also in crystalline schists.

Rutile. Titanic Oxide: TiO_2. Tetragonal; crystallizing in slender prisms and needles. Frequently twinned, on two types, producing geniculated and heart-shaped forms. Colour, yellow to red. Sp. G. = 4·20–4·27. Hardness = 6–6·5. Index of refraction, 2·759. Double refraction, very high. Unattacked by acids. Distinguished under the microscope by its yellow colour and strongly marked borders, due to the high index of refraction. It frequently presents a peculiar interlaced structure, known as *sagenite*. (See Fig. 68.) Rutile occurs as prisms and twins

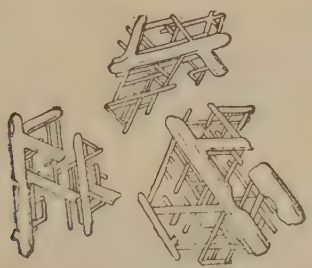


FIG. 68.

Crystals of Rutile (Sagenite). *After Rosenbusch.*

in the crystalline schists, especially in hornblende schist; also in sands and sedimentary rocks. Fine hair-like bodies occurring in clay and slates (*Thonschiefernädelchen*), are referred to rutile.[1]

Anatase. Titanic oxide: TiO_2. Tetragonal; with bipyramidal or tabular habit. Sp. G = 3·82–

[1] Teall: *Min. Mag.*, vol. vii., 1887, p. 201.

3·95. Hardness = 5·5 – 6. Index of refraction, 2·52. Double refraction, strong. Colour in thin section, yellow, brown or blue. Occurs in small quantities in granites and other igneous rocks, also in sands and clays derived from them.

CARBONATE GROUP.

Calcite. Carbonate of lime: $CaCO_3$; with CaO = 56 and CO_2 = 44 per cent. The carbonates of lime, magnesia and iron (calcite, magnesite and chalybite) are isomorphous, and can replace one another in any proportions. Rhombohedral. The crystalline forms assumed by calcite are innumerable: it occurs in rhombohedra, which may be either flat or have any degree of acuteness; in sharp-pointed scalenohedra (dog-tooth spar); in thick-set or slender six-sided prisms crowned by the faces of the rhombohedron; or in prisms terminated by the basal plane. It also occurs in amorphous masses, and in veins. Sp. G. = 2·72. Hardness = 3 (easily scratched with the knife). Index of refraction, 1·49–1·66. Cleavage parallel to the rhombohedron, perfect rhombohedra being produced by the fracture. Effervesces with acids. Colourless to white; but often stained yellow, red and brown by ferruginous impurities. Under the microscope it occurs in irregular grains, traversed by fine cleavage lines, intersecting at an acute angle. Very high double refraction. Between crossed nicols, the polarization colour is an iridescent pinkish grey of a high order; and broad colour-bands, produced by lamellar twinning, are often visible along the diagonals of the cleavage rhomboids.

As a secondary constituent, calcite occurs in the more basic igneous rocks—diorites, gabbros, dolerites, etc. It is the principal constituent of the altered limestones (marbles). It often forms the cementing material of fragmental rocks (*e.g.*, calcareous sandstones).

Chalybite or **Siderite.** Carbonate of iron: $FeCO_3$; with $FeO = 62{\cdot}1$, and $CO_2 = 37{\cdot}9$. Rhombohedral; isomorphous with calcite. Sp. G. $= 3{\cdot}83 - 3{\cdot}88$. Hardness $= 3{\cdot}5 - 4$. Index of refraction, 1·76. Double refraction, very high. Colour in thin section, grey, yellowish or brown. Occurs frequently in radially fibrous spherulites (spherosiderite).

Dolomite is a double carbonate of lime and magnesia: CaO, MgO, $2CO_2$. It resembles calcite in its crystallographic and optic properties. Index of refraction, 1·622. Double refraction, slightly higher than that of calcite. Chemically it is less soluble than calcite, being not acted upon by acetic acid or cold dilute hydrochloric acid. Sp. G., 2·8–2·9. Hardness $= 3{\cdot}5 - 4$.

Aragonite is the rhombic carbonate of lime: $CaCO_3$, with the same percentage composition as calcite. Its crystals are often six-sided, and, especially when twinned, resemble the hexagonal combination of prism and basal plane. Sp. G. $= 2{\cdot}9 - 3$. Hardness $= 3{\cdot}5 - 4$. Index of refraction, 1·631. Double refraction, slightly less than calcite. It is found in fibrous and spherulitic aggregates in many igneous and metamorphic rocks. It frequently fills cavities in basalt, or traverses the same rock in strings and veins. Stalactites are often built up of fibrous aggregates of aragonite. The small spherular bodies

which are formed in warm calcareous springs and give rise to pisolitic and oolitic rocks, consist of radiate and fibrous aragonite.

ZEOLITE GROUP.

Zeolites. A group of hydrated silicates of various bases: alumina, potash, soda, lime, baryta and strontia. They are secondary products, occurring in igneous rocks as the infillings of amygdaloidal cavities (especially of melaphyres and basalts), or as pseudomorphs after decomposed minerals (*e.g.*, nepheline).

Under the microscope the zeolites are always colourless, and occur in fibrous and radiate aggregates. They are easily decomposed by hydrochloric acid, with separation of gelatinous silica. The index of refraction of the zeolites is low (less than that of Canada balsam). All of them also exhibit low double refraction.

Some of the more commonly occurring varieties are: heulandite, natrolite, analcime, phillipsite, laumontite, scolecite and apophyllite. The composition of these is given in the following table:

Name.	Crystallographic System.	Formula.	Percentage Composition.					
			SiO_2	Al_2O_3	CaO	Na_2O	K_2O	H_2O
Heulandite	Monoclinic	$H_4CaAl_2(SiO_3)_6+3H_2O$	59.2	16.8	9.2	—	—	14.8
Natrolite	Rhombic	$Na_2Al_2Si_3O_{10}+2H_2O$	47.4	26.8	—	16.3	—	9.5
Analcime	Regular	$NaAl(SiO_3)_2+H_2O$	54.5	23.2	—	14.1	—	8.2
Phillipsite	Monoclinic	$(K_2Ca)Al_2(SiO_3)_4+4\frac{1}{2}H_2O$	48.8	20.7	7.6	—	6.4	16.5
Laumontite	Monoclinic	$H_4CaAl_2Si_4O_{14}+2H_2O$	51.1	21.7	11.9	—	—	15.3
Scolecite	Monoclinic	$Ca(AlOH)_2(SiO_3)_3+2H_2O$	45.9	26.0	14.3	—	—	13.8
Apophyllite	Tetragonal	$H_7KCa_4(SiO_2)_8+4\frac{1}{2}H_2O$	53.7	—	25.0	5.2	—	16.1

CHLORITE GROUP.

Chlorites. Hydrated silicates of magnesia, iron and alumina. Monoclinic (with pseudo-hexagonal symmetry). Gelatinize with hydrochloric acid. Sp. G. = 2·60–2·96. Hardness = 2–2·5. Colour, green: pleochroic in green and yellow tints. Occur in six-sided plates, scales, and fibres, sometimes united to spherular and spiral aggregates (*ripidolite* and *helminth*). Basal cleavage, less perfect than in mica; cleavage-flakes non-elastic. The double refraction is very low, the usual colour between crossed nicols being a grey or steel-blue of the first order. When heated on platinum foil chlorite becomes black and opaque.

Tschermak has divided the chlorites into **orthochlorites** and **leptochlorites**, according as they occur well crystallised or in fine scales and fibres. The orthochlorites he regards as mixtures of a serpentine molecule and an amesite molecule. The serpentine molecule (Sp) has the composition $H_4(MgFe)_3, Si_2O_9$, and the amesite molecule (At) that of $H_4(MgFe)_2, Al_2SiO_9$. The principal chlorites, then, may be represented thus:—

Pennine Clinochlore	} =	SpAt
Prochlorite	=	Sp_3At_{17}
Corundophilite	=	$SpAt_4$
Amesite	=	At

Chlorite is essentially a secondary mineral resulting from the decomposition of dark mica, hornblende and augite. It occurs abundantly in altered igneous

rocks, especially in the more basic types such as gabbro, diabase, melaphyre, etc., which largely owe their greenish colour to this mineral; also in epidiorites and chlorite-schists. It is sometimes confounded, under the microscope, with secondary hornblende and with serpentine, with which it is often associated and which it much resembles. It may be distinguished from the former by its low double refraction, and from the latter by its pleochroism.

OTHER HYDRATED SILICATES.

Serpentine. Hydrated silicate of magnesia and iron; $2H_2O, 3(MgFe)O, 2SiO_2$. Rhombic or monoclinic. Sp.

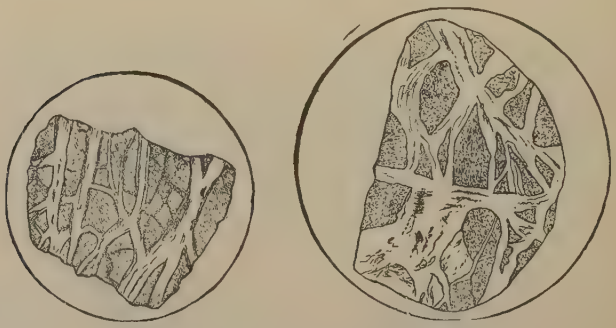


FIG. 69. FIG. 70.

Olivine altering into Serpentine.
(*After Bonney.*)

G. = 2·5 - 2·7. Hardness = 3 – 4. Colour, dull green; often stained red and yellow with iron oxides. Index of refraction, 1·57. Double refraction, moderate. Straight extinction between crossed nicols. Occurs as an altera-

tion-product of olivine, hornblende and augite. Under the microscope it usually presents a confusedly interlaced aggregate of colourless blades, scales and fibres, which frequently enclose unaltered fragments of the mineral from the alteration of which it takes its origin. (See Figs. 69 and 70.) Serpentine derived from olivine possesses a "mesh structure"; that arising from hornblende is "bladed," while augite often gives rise to a "netted" form of the mineral (*antigorite*). *Pseudophite* is an aluminous variety of serpentine produced by the alteration of the felspar in gabbro. Veins of fibrous serpentine (*chrysotile*) are worked as a source of commercial asbestos.

Talc. Hydrated silicate of magnesia: H_2O, $3MgO$, $4SiO_2$, with $SiO_2 = 63{\cdot}5$, $MgO = 31{\cdot}7$, and $H_2O = 4{\cdot}8$ per cent. Rhombic; but with pseudo-hexagonal symmetry. Sp. G = 2·7–2·8. Hardness = 1. Index of refraction, 1·545; double refraction, very high (between muscovite and zircon). Scratched by the finger-nail. Pale-green or colourless. Cleavage, basal. Flakes, flexible, but non-elastic. In thin section, it is found in colourless scales, resembling muscovite. It occurs as an alteration-product of magnesian minerals, mainly in metamorphic schists (talc-schist). *Steatite* or *soapstone* is a variety of talc.

Ottrelite and **Chloritoid.** Hydrated silicates of alumina, iron, magnesia, or manganese. Ottrelite is probably represented by the formula $H_2O(FeMn)O$, Al_2O_3, $2SiO_2$, while chloritoid is H_2O $(FeMg)O$, Al_2O_3, SiO_2. Monoclinic; but with pseudo-hexagonal symmetry, like mica. Sp. G. = 3·52 – 3·57. Hardness = 6·5. Index of refraction, 1·74. Double refraction,

high, same as that of hornblende. Colour, bluish-green. Pleochroism in bluish and green tints: a, olive green; β, plum colour to indigo blue; γ, yellowish green to colourless. Occur in lustrous 6-sided plates in metamorphic schists. Under the microscope, characterized by lamellar twinning.

Kaolinite. Hydrated silicate of alumina: $2H_2O$, Al_2O_3, $2SiO_2$; with $SiO_2 = 46{\cdot}5$, $Al_2O_3 = 39{\cdot}5$, $H_2O = 14{\cdot}0$. Monoclinic; but with pseudo-hexagonal symmetry. Sp. G. = 2·6–2·63. Hardness = 2–2·7. Cleavage, basal. Index of refraction, 1·56. Double refraction, low—a means of distinction from

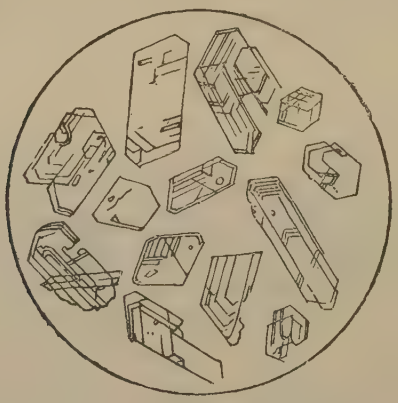


FIG. 71.
Crystals of Kaolinite, under the microscope. (*After Teall.*)

muscovite. Occurs in colourless six-sided plates and scales, resembling muscovite, in pockets in quartz veins at Amlwch in Anglesey, and at the National Bell Mine, Silverton, Colorado. It is probably one of the decomposition products of felspar.

CONTACT MINERAL GROUP.

Andalusite. Silicate of alumina: Al_2O_3, SiO_2, with $SiO_2 = 36{\cdot}8$ and $Al_2O_3 = 63{\cdot}2$ per cent. Rhombic. In square thick-set prisms, terminated by the basal plane. Sp. G. = 3·1–3·2. Hardness = 7–7·5. Index of refraction, 1·638. Unattacked by acids.

Crystals of this mineral usually appear dark-coloured, owing to the presence of included carbonaceous matter. Under the microscope, however, the grains are either colourless or pink;

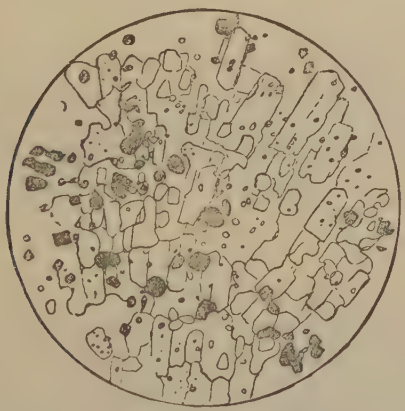


FIG. 72.
Andalusite, under the microscope. (*After Cohen.*)

in the latter case, they often present a marked pleochroism (pale-yellow or pale-green to rose-red). The pleochroism is sometimes manifested in irregularly distributed spots and patches. Double refraction, slightly higher than that of quartz, but less

than sillimanite, which it resembles. Occurs in slates and shales that have undergone metamorphism in contact with granite; also in gneisses and crystalline schists, and as an accessory constituent of granite (*e.g.*, at the Cheesewring in Cornwall). **Chiastolite** is a variety of andalusite, containing graphitic material arranged along the diagonals of the prism. Occurs in small light-coloured prisms in chiastolite-slate in the neighbourhood of granite (*e.g.*, Skiddaw).

Sillimanite. Silicate of alumina: Al_2O_3, SiO_2, with $SiO_2 = 36{\cdot}8$ and $Al_2O_3 = 63{\cdot}2$ per cent., like andalusite. Rhombic. Habit, prismatic without definite terminal faces, often in long and slender crystals; sometimes fibrous (fibrolite). Cleavage parallel to the brachypinacoid, perfect. Sp. G. = 3·23–3·24. Hardness = 6–7. Unattacked by acids. Colour, brown to greyish green; in thin section, colourless. Index of refraction, fairly high (1·667); double refraction, moderately high, higher than that of andalusite. Occurs in gneisses and crystalline schists, often in the aureoles of contact metamorphism around granite, in association with cordierite, corundum, andalusite and kyanite.

Kyanite. Silicate of alumina: Al_2O_3, SiO_2, with $SiO_2 = 36{\cdot}8$ and $Al_2O_3 = 63{\cdot}2$ per cent., like sillimanite and andalusite. Triclinic; usually in long prismatic crystals. Cleavage parallel to the orthopinacoid, perfect, with partings parallel to the basal plane. Sp. G. = 3·5–3·7. Hardness = 4–7. Colour, white to blue. In thin section, colourless to pale blue, with weak pleochroism. Index of refraction, high (1·72); double refraction, low. Kyanite occurs in gneisses

and crystalline schists in association with garnet, staurolite and sillimanite; often in the aureoles of contact metamorphism round granite. It is also found in sands and clays in association with rutile, tourmaline, zircon, etc. According to Vernadsky, kyanite, when heated to 1300° C., is converted into sillimanite.

Staurolite. Hydrated silicate of alumina, iron and magnesia: $2H_2O,6(FeMg)O,12Al_2O_3,11SiO_2$. Rhombic. In prismatic forms terminated by the basal plane; commonly twinned, forming symmetrical Maltese and St Andrew's crosses. Sp. G. = 3·3–3·8. Hardness = 7–7·5. Index of refraction, high (1·74), double refraction, slightly higher than quartz. Unattacked by acids. Occurs in the crystalline schists, and in rocks of the granite contact-zone.

Cordierite. Hydrated silicate of alumina, iron and magnesia: H_2O, $4(MgFe)O$, $4Al_2O_3$, $10SiO_2$. If the ratio Mg : Fe = 7 : 2, then $SiO_2 = 49·4$, $Al_2O_3 = 33·6$, $FeO = 5·3$, $MgO = 10·2$, and $H_2O = 1·5$ per cent. Rhombic; with pseudo-hexagonal symmetry. Sp. G. = 2·60–2·66. Hardness = 7–7·5. Double refraction, slightly lower than that of quartz. Often twinned. Colour, dark blue; in thin section usually colourless. Feeble pleochroism when coloured. Yellow pleochroic spots or halos surround inclusions of zircon and apatite, but disappear on rotation of the section; they vanish on heating. Cordierite may be distinguished from andalusite by its lower index of refraction (1·536), a grain placed in Canada balsam being scarcely visible, whereas andalusite stands out with well-marked contours.

Cordierite occurs in rounded grains, with complex twinning producing radial extinction, in granites and

metamorphic rocks (cordierite-gneiss or cordierite-schist); more rarely in volcanic rocks (*e.g.*, basalt, andesite). It alters easily into mica-like decomposition products (pinite, esmarkite, praseolite, gigantolite, etc.).

Idocrase or **Vesuvianite**. Hydrated silicate of lime and alumina: probably H_2O, $12CaO$, $3Al_2O_3$, $10SiO_2$. Also small quantities of manganese, iron, magnesium and alkalies, are often present. Tetragonal. In square prisms, with basal plane and pyramid. Sp. G. = 3·35–3·45. Hardness = 6·5. Colour, dark green, brown, red, yellow. Lustre, vitreous. Index of refraction, high (1·72); double refraction, weak. Occurs in limestones that have undergone alteration by contact with igneous rocks.

Axinite. A borosilicate of calcium and aluminium: $7CaO$, $2Al_2O_3$, B_2O_3, $8SiO_2$, in which lime may be partially replaced by manganese, iron, and magnesium. Triclinic. In broad crystals with acute edges. Cleavage parallel to the brachypinacoid, distinct. Sp. G. = 3·271–3·29. Hardness = 6·5–7·0. Colour, honey-yellow to clove-brown. In thin section, colourless to pale-yellow or violet. Faint pleochroism. Index of refraction, high (1·677); double refraction, the same as quartz. Occurs in the contact-aureoles round granite.

Topaz. A silicate and fluoride of aluminium: $Al_2O_2(O,F_2)SiO_2$. If the ratio of $O : F_2 = 5 : 1$ then $SiO_2 = 33·3$, $Al_2O_3 = 56·5$, $F = 17·6$, deducting O for $F_2 = 7·4$.

Rhombic; with short prismatic habit and pyramidal and basal terminations. Basal cleavage, perfect. Sp. G. = 3·5–3·57. Hardness = 8. Colourless, wine-yellow

or tinted blue, red or green. In thin section, colourless. Index of refraction, 1·62. Double refraction, the same as quartz. The lower double refraction is a means of distinction from sillimanite. Occurs in some granites and pegmatites; also in the aureoles of contact-metamorphism round granite.

Datolite. A basic orthosilicate of calcium and boron: $H_2O,2CaO,B_2O_3,2SiO_2$ with $SiO_2 = 37·6$, $B^2O_5 = 21·8$, $CaO = 35·0$ and $H_2O = 5·6$ per cent.

Monoclinic. In stumpy, prismatic forms; or in irregular grains. Cleavage, ill-defined. Fracture, conchoidal to uneven. Sp. G. = 2·9–3·0. Hardness = 5–5·5. Colourless in thin section. Index of refraction, moderate (1·65). Double refraction, very strong, between that of muscovite and talc. Occurs in association with zeolites and calcite in the amygdaloidal cavities of basalt; also in zones of contact-metamorphism. Datolite may be distinguished from topaz, andalusite and wollastonite by its very strong double refraction.

Corundum. Alumina: Al_2O_3. Hexagonal. In hexagonal prisms terminated by the basal plane or in steep hexagonal bi-pyramids. Parting or pseudo-cleavage, parallel to the basal plane. Fracture, uneven to conchoidal. Index of refraction, high. Double refraction, the same as that of quartz. Often colourless in thin section. When coloured, the colour is unevenly distributed in spots or streaks. The blue variety is *sapphire;* the red, *ruby*. With strong colouration, pleochroism is observable.

Corundum occurs in rocks rich in alumina — in granite, syenite, nepheline-syenite, etc.; also in

pegmatite. It is developed in zones of contact-metamorphism especially in argillaceous limestones.

Corundum may be distinguished from quartz, nepheline and apatite, which it resembles in regard to double refraction, by its higher index of refraction.

PART III.

THE CLASSIFICATION OF THE IGNEOUS ROCKS.

CHAPTER I.

THE PLUTONIC ROCKS.

To produce a satisfactory classification of the igneous rocks, a classification which shall be at once simple and comprehensive, is one of the most difficult problems the petrologist can attack. The various types are so intimately related that any attempt at rigid and systematic arrangement is not likely to meet with a great measure of success. But some method of grouping rocks is a necessity that must be faced. As explained on pages 5 and 6, the most convenient primary division of the igneous rocks is into plutonic, hypabyssal and volcanic. The further classification adopted here is one based mainly on chemical considerations.

It has been found that the best results are obtained by arranging the rocks in the order of their silica contents. With this arrangement should be combined a division into series according to the alkali and calc-alkali contents, as shown by the constituent felspars and felspathoids.

Arranged in the order of their silica contents, the plutonic rocks can be divided into three groups:

1. **Acid**, with silica contents above 66 per cent.
2. **Intermediate**, with silica contents between 66 and 52 per cent.; and
3. **Basic**, with silica contents below 52.

These limits are, of course, quite arbitrary, but it will be seen later that they permit a convenient separation in accordance with existing records of rock types. At the extreme basic end there is a small assemblage of rocks which contain very little or no felspar. These rocks (the picrites, peridotites, hornblendites and pyroxenites) consist of ferromagnesian minerals and iron-ores. They form a sub-group generally known as the **ultrabasic** rocks. They need not be considered here in the general scheme of classification.

The division according to alkali and calc-alkali contents is accomplished by means of the felspars and felspathoids, the variation in which enables the formation of a number of series, each series being characterised by its dominant felspar or felspathoid, and each comprising acid, intermediate and basic rocks. Thus, a series can be formed which is characterised by the predominance of the lime-bearing felspars (oligoclase to anorthite). This may be conveniently termed the **calc-alkali series**. It comprises rocks ranging from granodiorite through tonalite and diorite to gabbro, according to the percentage of silica. In contrast with this is the **alkali series**, in which there is a dominant alkali-felspar (orthoclase, microperthite, soda-orthoclase, microcline,

anorthoclase, or albite, etc.), or by a felspathoid (nepheline, sodalite, etc.). Occupying a middle position between the calc-alkali and the alkali series is the **monzonite series**, which comprises rock types characterised by the presence of both orthoclase and a lime-bearing plagioclase without either being greatly predominant.

Although in Nature there is a perfect gradation in each of these series from a most acid to a most basic type, yet for classificatory purposes it is convenient to break them up into three divisions corresponding to the Acid, Intermediate, and Basic groups as above defined. By doing this the following scheme of classification is obtained:

SCHEME OF CLASSIFICATION OF THE PLUTONIC ROCKS.

	Alkali Series.	*Monzonite Series.*	*Calc-alkali Series.*
Acid Group	GRANITE	ADAMELLITE	GRANODIORITE
Inter-Group	SYENITE	MONZONITE	DIORITE
Basic Group	ALKALI-GABBRO	KENTALLENITE	GABBRO

The alkali series may be further sub-divided into:

1. A *potash series*, with predominant potash-felspar

(orthoclase, microcline)—*e.g.*, potash-granite, potash-syenite, shonkinite.

2. A *soda series*, with a predominant soda-felspar (anorthoclase, soda-orthoclase, albite); or with a soda-lime felspar in combination with nepheline, and soda-pyroxenes and soda-amphiboles—*e.g.*, soda-granite, soda-syenite, essexite.

3. A *felspathoid series*, in which nepheline, sodalite, or allied felspathoid, is largely developed, and felspar subordinate—*e.g.*, nepheline-syenite, nepheline-gabbro.

It will be seen by reference to the table that there is continuity of types both vertically (in series) and horizontally (from series to series). For example, not only do the granodiorites pass by decreasing silica-content into diorites and thence into gabbros, but they pass also, by decreasing lime and increasing alkalies, into the adamellites and thence into the alkali-granites or granites proper: and similarly for each series and for each group. The divisions are adopted for convenience, but they do not represent actual hard and fast lines existing in Nature.

The affinities of the various members of a continuous series, or members of different series in the same group can be shown graphically by Iddings'[1] method, in which the molecular proportions of the silica are represented by abscissæ and those of the bases by ordinates (see Fig. 78), or by Brögger's[2] modification of Michel-Levy's[3] method, by which the molecular ratios

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[1] Iddings: *Bull. Phil. Soc. Washington*, vol. xi., pp. 191-220.

[2] Brögger: Das Ganggefolge des Laurdalits, *Vidensk. Skrifter I. Math.-natur. Klasse*, 1897, No. 6., p. 257.

[3] Michel-Levy: *Bull. d. serv. de la carte geol. de la France*, No. 57, vol. ix. (1897).

are plotted so as to give a characteristic picture of the rock type. In Brögger's modification the molecular ratios are plotted on axes radiating from a central point: four of these are formed by a vertical and a horizontal line, and four by lines forming an angle of 120° with the vertical and horizontal lines. On the horizontal line the molecular proportion of the silica is laid off[1] half to the right and half to the left. On the vertical line the alumina is laid off downward, the lime upward. The ratios for the iron (FeO) and magnesia are laid off on the oblique axes above, and the soda and potash below the horizontal line. By joining the points thus obtained, a picture of the rock is produced, the shape of which at once shows the chemical character of the rock.

An example will make the matter clear. Suppose a diorite to have the percentage composition represented by the figures in column I. of the following table, then the molecular proportions, obtained by dividing percentage by molecular weight, will be as shown in column II., and the lengths to be laid off in millimetres as shown in column III.

	I.	II.	III.
SiO_2	56·52	·942	47
Al_2O_3	16·31	·16	16
[2] Fe_2O_3	4·28		
FeO	5·92	·082	8·2
MgO	4·32	·108	10·8
CaO	6·94	·124	12·4
Na_2O	3·43	·055	5·5
K_2O	1·44	·015	1·5
H_2O	1·03		

[1] A convenient scale is 100 millimetres to the unit.

[2] The ferric oxide (Fe_2O_3) can be plotted on the FeO line and beyond the FeO; but this is not essential to the present purpose.

Plotting these results in the manner described, the diagram marked II in figure 73 is obtained :—

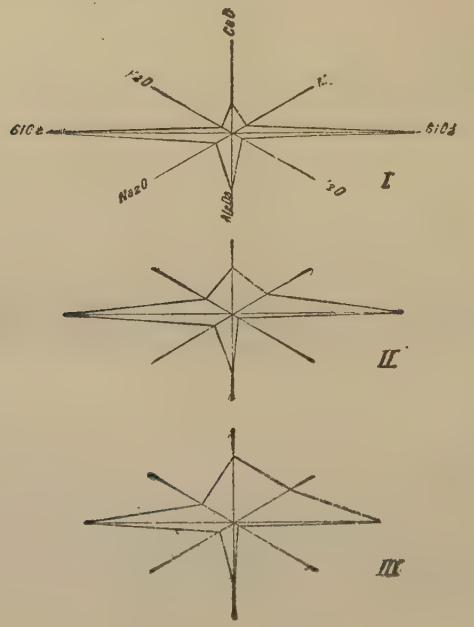

FIG. 73.

Diagrams for three typical members of the Calc-alkali Series. I. Granodiorite ; II. Diorite ; III. Gabbro.

In the same figure the molecular proportions of a granodiorite and a gabbro are shown, and an interesting comparison may be made. The increase in lime and magnesia, and decrease in alkalies with increasing basicity, are well shown. In figure 74 are similar plots of the molecular proportions of a

diorite, a monzonite, and a soda-syenite. These illustrate the variation from series to series in the same (in this case, the intermediate) group. The figures show the comparatively high lime, magnesia and iron in the representative of the

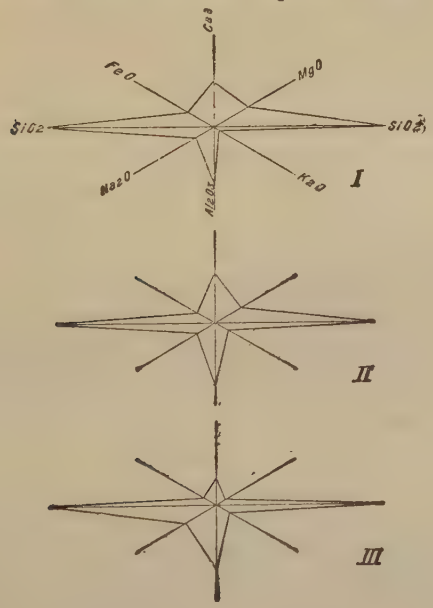

FIG. 74.

Diagrams for three typical members of the Intermediate Group. I. Diorite; II. Monzonite; III. Soda-Syenite.

calc-alkali series, the greater proportion of alkalies without diminution of lime in the monzonite series, and the greatly increased alkalies with diminished lime, magnesia and iron in the representative of the alkali series.

The division of the igneous rocks into series is justified by the fact that although the assemblage of rocks in any given area of the earth's surface may range from quite basic to very acid types, they usually have chemical characters in common which place them in a definite series. Thus, for example, the whole chain of the Andes in South America, the corresponding coast-ranges (the Sierra Nevada, etc.) and the main chain of the Rocky Mountains in the Western States of North America, are characterized by the occurrence of rocks belonging to the calc-alkali series, namely, granodiorites and diorites among the plutonic rocks, and their corresponding volcanic equivalents—the andesites; while the hill ranges east of the Rockies (in Montana and other Central States)[1] and of the Andes (*e.g.*, in the Argentine and Paraguay) present types progressively richer in alkalies. Again, over large areas of the eastern portion of the African Continent and in the adjacent islands, the prevailing types belong to the alkali series.[2] In smaller areas, well-named by Professor Judd,[3] *petrographical provinces*, the prevalence of types belonging to a

[1] Pirsson: Petrographical Province of Central Montana *Amer. Journ. of Sci.*, vol. xx., 1905, p. 36.

[2] Lacroix: *Nouv. Arch. d. Muséum*, 4me. ser., vols., 1902, 1903. See also an interesting paper on this subject by G. T. Prior: Comparison of Volcanic Rocks from the Great Rift Valley with rocks from Pantelleria, the Canary Islands, Ascension, St. Helena, Aden and Abyssinia, *Journ. of the Min. Soc.*, vol. xiii., 1903, p. 228.

[3] J. W. Judd: On the Ancient Volcano of the district of Schemnitz, *Quart. Journ. Geol. Soc.*, vol. xxxii., 1876, p. 292.

definite series is also shown. Thus the Kola Peninsula[1] and New England[2] may be quoted as examples of alkali provinces. On the other hand, the occurrence in a limited area of members of the calc-alkali series is exemplified by the plutonic complex of Garabal Hill, near Loch Lomond,[3] which comprises rocks ranging from hornblende-biotite granite through tonalite and diorite to peridotites. As a whole the British Isles constitute a calc-alkali province; but there are certain limited areas in which alkali rocks predominate (*e.g.*, Cornwall, Leinster, and the neighbourhood of Loch Borolan, in Scotland). The rocks composing the Brocken granite *massif* in the Harz,[4] (hornblende-biotite-granite, tonalite, diorite, and gabbro), are another example.

It was Rosenbusch[5] who, by extending Durocher's[6] hypothesis of the liquidation of the original earth magma into two zones consisting of an upper acid and a lower basic magma, first formulated the theory that the plutonic rocks have been produced from a number of partial magmas which themselves were differentiated from an originally homogeneous earth-magma (*Urmagma*). From the magma-basins in

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[1] W. Ramsay and V. Hackman: Das Nephelin-syenit-gebiet auf Kola, *Fennia*, vol. xi., No. 2, Helsingfors, 1894.

[2] H. S. Washington: *Journ. of Geol.*, 1898.

[3] Dakyns and Teall: *Quart. Journ. Geol. Soc.*, vol. xlviii., 1892, p. 104.

[4] Lossen: *Zeits. D. Geol. Gesell.*, vol. xxxii., 1880, p. 206.

[5] H. Rosenbusch: *Tschermak's Min. Pet. Mitth.*, vol. xi., 1890, p. 144.

[6] J. Durocher: *Ann. d. Mines*, ser. 5, vol. xi., 1857, p. 217.

which these earliest separated products had accumulated, later differentiations also arose, perhaps under the influence of the pressure due to earth movements in a sinking area, as postulated by Brögger for the Christiania district.[1]

According to Rosenbusch's theory, the first step in rock evolution consisted in the differentiation of the original earth-magma into two classes of secondary magmas: (1) Those rich in alkalies which he designated the nepheline-syenite (*foyaitische*) and theralite magmas, and (2) those poorer in alkalies, but richer in lime and magnesia, which he called the granito-diorite and gabbro-peridotite magmas. This division corresponds almost exactly to the alkali and calc-alkali rock series, and Rosenbusch adopts these names for the magmas in the last edition of his *Mikroskopische Physiographie* (vol. ii., 1907).

The recognition of the existence of an intermediary or connecting magma giving rise to the monzonite rock series, the members of which present affinities sometimes to the alkali, and sometimes to the calc-alkali series, we owe to Brögger's classic work in Southern Tyrol and in the Christiania district.

THE GRANITE FAMILY.

The granite[2] family is by far the largest division of the plutonic rocks, for it comprises all rocks of

[1] Die Triadische Eruptionsfolge bei Predazzo: *Vidensk. Skrifter I. Math.-natur. Klasse*, 1895, p. 177, and The Basic Eruptive Rocks of Gran, *Quart. Journ. Geol. Soc.*, vol. l., 1894, p. 15.

[2] The word *granite* was first used by Cæsalpinus in the year 1596.

deep-seated origin with over 66 per cent. of silica. In general terms, the members of this family may be characterized as consisting of a holocrystalline, and as a rule coarsely crystalline, aggregate of quartz, two or more felspars, and one or more varieties of mica, hornblende or augite. Accessory minerals are numerous: apatite, zircon, sphene, orthite, rutile, garnet, topaz, cordierite (pinite), cassiterite, tourmaline, fluorspar, molybdenite, hæmatite, magnetite and iron-pyrites being among them. Resulting from the decomposition of the original constituents (and especially of the felspar) are sericite, talc, kaolin, epidote, calcite, chlorite and serpentine.

The essential minerals can be easily distinguished in the hand-specimen: the quartz by its vitreous lustre, pellucidity, conchoidal fracture and absence of cleavage; the felspars by their large and lustrous cleavage surfaces, their twinning and their opaque white or pink colour; and the micas by their brilliant lustre, platy cleavage, and characteristic colour, silvery white for muscovite, brownish-black for biotite. Hornblende, when present, is a black or dark green variety, with the usual prismatic cleavage, the cleaved surfaces meeting at an angle of 124 degrees.

With regard to structure, the granitic structure is typically one in which the component minerals are equidimensional and devoid of crystal faces, each grain having common boundaries with its neighbours, as if formed by simultaneous crystallization. Frequently, however, some of the felspar occurs as large, well-shaped phenocrysts embedded in a holocrystalline groundmass of quartz, felspar and mica (*porphyritic*

granite). The size of the individual grain varies considerably. Often a granite is coarse-grained in the interior of the mass, and fine-grained in its marginal portions, where cooling has progressed more rapidly. A parallel arrangement of the constituents, especially when the felspars are idiomorphic, or are developed porphyritically, betrays flow-movements in the partially consolidated granite magma, and is sometimes accompanied by protoclastic granulation; but such flow-structures must be distinguished from the foliation produced by differential movements due to earth stresses after consolidation. In such foliated granites (*gneissose granites, augen-gneiss*), "nuclei" of the original quartz or felspar are surrounded by granular aggregates of cataclastic quartz and felspar, the whole forming eye-like masses wrapped round by fibrous and ribbon-like laminæ of white mica.

A common feature is the presence of dark patches or "heathen," as they are termed by the quarrymen. These patches, which are mostly of irregular shape, are composed of ferromagnesian minerals, iron-ores, and a little plagioclase felspar. Their origin has been the subject of some controversy. J. A. Phillips[1] considered them to have arisen by a segregation of the more basic constituents of the granite; but it is probable that in the majority of cases they are fragments (xenoliths) of pre-existing rocks caught up and enclosed by the granite magma. The spheroidal aggregations of plagioclase, dark mica, hornblende and

[1] *Quart. Journ. Geol. Soc.*, vol. xxxvi. (1880), p. 1, and vol. xxxviii. (1882), p. 216.

magnetite round a central nucleus, with both radial and concentric structure, have, however, undoubtedly been formed by concretion during the consolidation of the granite magma. The spheroid-granite of Mullaghderg in County Donegal is a well-known example.[1]

Granite occurs as bathyliths, laccoliths, and stocks, often forming the central core of a mountain range, and surrrounded by an aureole of rocks which present unmistakable evidence of the metamorphism produced by heat, or in some cases by the fluoric and boric emanations accompanying the intrusion. Within this contact zone, which, in the case of a large granite *massif* intruded into folded rocks, may have the width of a mile or more, the rocks are crumpled, baked and altered into hornstone. In slates characteristic contact-minerals are developed—biotite, muscovite, chlorite, ottrelite, tourmaline, chiastolite, andalusite, corundum, kyanite, cordierite, sillimanite, and staurolite. The development of these minerals in the portion of the contact zone furthest removed from the the granite often assumes the character of spots and knots in the slates. The metamorphism round the Leinster, Cornish and Skiddaw granites, and that produced by the intrusion of the newer granites of the Highlands may be cited. In the case of calcareous rocks, limestones are converted into marble, with development of lime-silicates, as for example, the minerals wollastonite, idocrase, diopside and lime garnet; while calcareous shales yield lime-silicate

[1] Hatch: *Quart. Journ. Geol. Soc.*, vol. xliv., 1888, p. 548, with a summary of the literature on spheroid-bearing granites.

rocks (the *kalksilikat-hornfels* of the Germans). The Coniston limestone, where it is in contact with the Shap granite at Wasdale Head, affords a good example of this kind of contact-metamorphism. Similar phenomena may be seen around the Dartmoor, St. Austell and Bodmin Moor granites.

The Classification of the Granites.

The granites are usually divided according to the nature of their ferromagnesian minerals into:—*granite proper*, with both light and dark mica; *muscovite-granite*, with white mica alone; *biotite-granite*, with dark mica alone; *hornblende-biotite-granite*, with hornblende in addition to dark mica; *hornblende-granite*, with hornblende alone; *augite-granite*, with augite in addition to biotite or hornblende. Since the number of combinations of these minerals is very great, the classification is a clumsy one, and it is much more convenient to classify the granites according to the felspar content. As already explained, the granites may be divided, according to the relative proportion of alkali and soda-lime felspars, into an *alkali-family*, with predominating alkali felspars, a *calc-alkali family* (the granodiorites), with predominating lime-bearing plagioclase, and, forming a connecting link between these two extremes, a family in which neither alkali nor soda-lime felspar greatly predominate (the *adamellite family*). The dividing lines between these three families must of necessity be drawn arbitrarily; but practical limits may be fixed by assigning those

granites, in which less than two-thirds and more than one-third of the total felspar content is alkali-felspar, to the adamellite family; while those with alkali-felspar, amounting to more than two-thirds of the total felspar, rank with the alkali-granites, and those with less than one-third with the granodiorites.

The Alkali-Granite Sub-Family.

The alkali-granites may be again sub-divided according to the nature of the alkali-felspar into the potash-granites, in which the predominating felspar is a potash felspar (orthoclase, perthite or microcline), and the soda-granites [1] in which the predominating felspar is a soda-felspar (soda-orthoclase, anorthoclase, or albite).

The potash-granites contain abundant muscovite, either alone or in association with dark mica. The former occurs in small lustrous flakes without crystal contours. The dark mica is biotite or more rarely a lithia-bearing mica (lithionite). It is strongly pleochroic, in brown or reddish-brown to pale yellow colours, and often contains numerous enclosed zircons with pleochroic halos. The dominant mineral is the potash-felspar, sometimes in large phenocrysts, usually twinned on the Carlsbad type. It may be orthoclase, perthite or microcline. The latter is recognisable under the microscope by its

[1] The name *soda-granite* was first used by Prof. Haughton in describing some of the Leinster granites. *Trans. Roy. Irish Acad.*, vol. xxiii. (1859), p. 608.

characteristic cross-hatching. Enclosures of other minerals, black mica, zircon, apatite, etc., are common; and alteration products, such as muscovite and kaolin, are usual. A soda-lime felspar (usually oligoclase) accompanies, but is subordinate to, the potash felspar, Its twin-lamellation between crossed nicols affords a ready distinction.

The true **soda-granites** are comparatively rare. They are characterized by the predominance of soda silicates. Soda-orthoclase and anorthoclase or albite are the dominating felspars; and with these are associated various soda-amphiboles (arfvedsonite, riebeckite, glaucophane and hastingsite) and soda-pyroxenes (ægirine, ægirine-augite and acmite). Different types are usually distinguished by prefixing the name of the dominant amphibole or pyroxene thus:—riebeckite-granite, ægirine-granite, etc. With decreasing silica the soda-granites grade into the soda-syenites, or, if nepheline be developed, into nepheline-syenites.

For rocks which consist of quartz and alkali-felspar without an appreciable quantity of ferro-magnesian minerals, Spurr has suggested the name *alaskite*.[1] The chemical composition of some typical alkali-granites is given on page 167.

The Adamellite Sub-Family.

Here are included the granites in which the lime-bearing plagioclase felspar either equals the alkali-felspar in quantity, or is not greatly subordinate thereto. The potash-mica (muscovite) is usually

[1] Spurr: *Amer. Geol.*, April, 1900, p. 230.

Analyses of Alkali-Granites.

	I. Soda-granite Croghan Kinshela.	II. Potash-granite Cairngorm.	III. Potash-granite Lamorna.	IV. Potash-soda-granite, Botallack.	V. Soda-granite Hougnatten.
SiO_2 - -	80.24	76.01	74.69	74.54	71.65
Al_2O_3 - -	12.24	13.47	16.21	14.86	13.04
Fe_2O_3 - -	0.72	1.54	tr.	2.53	2.79
FeO - -	—	—	1.16	0.23	1.80
MgO - -	—	.06	.48	—	tr.
CaO - -	0.89	.54	.28	0.29	tr.
Na_2O - -	5.58	2.32	1.18	3.49	6.30
K_2O - -	0.40	5.57	3.64	3.73	3.98
H_2O - -	—	.56	1.23	.87	1.10
TiO_2 - -	—	—	—	—	—
Other constit.	—	.12	.68	—	—
	100.07	100.19	99.55	100.54	100.66

I. Soda-granite, Croghan Kinshela, Mount Leinster (S. Haughton).
II. Potash-granite, Cairngorm, Central Highlands, Scotland (W. Mackie).
III. Potash-granite, Lamorna, Cornwall (W. Pollard).
IV. Potash-soda-granite, Botallack, Cornwall (J. A. Phillips).
V. Soda-granite (Brögger's *Natron-granit*) Hougnatten, Lougenthal, Norway (L. Schmelc).

absent, while biotite, either alone or in combination with a dark brownish-green hornblende, is abundant.

The name adamellite was proposed by Brögger[1] for the most acid division of the monzonite series, which corresponds in respect of acidity to the granodiorites of the calc-alkali series, and to the potash and soda-granites of the alkali series. It includes most of the rocks known as biotite-granite and hornblende-biotite-granite, which grade on the one side into the granodiorites, and on the other into the

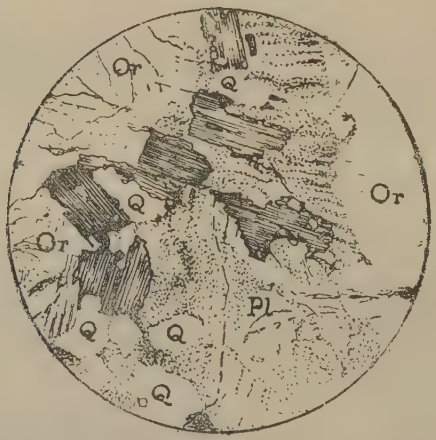

FIG. 75. Biotite-granite Shap (adamellite) composed of orthoclase (Or.), plagioclase (Pl.), quartz (Q.), and biotite (the dark mineral). *(From a photograph by R. H. Rastall.)*

[1] Die Triadische Eruptionsfolge bei Predazzo, *Vidensk. Skrifter I. Math.-natur. Klasse*, 1895, p. 61. The name *adamellite* was used many years ago by Cathrein for the rocks now known as tonalite; but the name never came into general use, and there is, therefore, no valid objection to its being used in Brögger's sense.

alkali-granites, according as lime-bearing plagioclase or alkali-felspar predominates. For practical purposes Lindgren's [1] useful suggestion may with a small modification be adopted, namely, that a rock in which less than one-third of the felspar is orthoclase would then be classed with the granodiorites (or with the diorites when the silica is less than 66 per cent.), and one with more than two-thirds of orthoclase, with the granites (or syenites when SiO_2 is less than 66 per cent.). Only rocks of which between one-third and two-thirds of the total felspar is orthoclase, would be referred to the adamellite (or monzonite) family.

The Granodiorite Sub-Family.

This division of the granite family is characterized by the great predominance of a lime-bearing plagioclase (basic oligoclase or andesine) and the subordination of alkali-silicates. Orthoclase is always present in small quantity: it must not exceed one-third of the total felspar content.

The name "granodiorite" was first proposed in 1892 by G. F. Becker in conjunction with H. W. Turner [2] and W. Lindgren.[3] These authors have defined the type as a light-grey granitic rock in which soda-lime felspars (basic oligoclase or andesine) largely

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[1] W. Lindgren: *Amer. Journ. of Sci.*, 1900, p. 269.

[2] H. W. Turner: "The Rocks of the Sierra Nevada," *14th Ann. Rep. U.S. Geol. Surv.*, 1894, p. 478 and 482.

[3] W. Lindgren: *Amer. Journ. of Sci.*, Series 4, vol. iii., 1897, p. 308, and 1900, Series 4, vol. ix., p. 269.

predominate over orthoclase, the remaining essential constituents being quartz, biotite, and usually hornblende, together with sphene, apatite and magnetite. It occurs in association with tonalite, diorite and gabbro, and no doubt represents the extreme acid end of the gabbro-diorite series. According to Lindgren, the percentage of silica, which rises as high as 73 per cent., may fall as low as 59 per cent., and he makes the distinction from the more acid members of the diorite family depend on the orthoclase. But most, if not all, diorites contain some small quantity of orthoclase, and it is better for practical purposes to make the percentage of silica the means of dividing the granodiorites from the diorites, and to call no rock with less than 66 per cent. of silica a granodiorite. The ferromagnesian minerals are biotite, hornblende, and sometimes augite, with sphene, apatite and magnetite as accessory constituents. Some hornblende-biotite-granites belong here. By decreasing silica the granodiorites pass into the tonalites and quartz-diorites. Rocks of this type occur abundantly in the Andes (*Andes granite*)[1] and in the Sierras of California, but are otherwise not of very common occurrence. They occur possibly among the plutonic complexes of the Central Highlands in association with tonalite, diorite and gabbro, and also perhaps among the old plutonic gneisses of the North-West Highlands. The chemical composition of some typical granites of the adamellite and granodiorite types is given on page 171.

[1] O. Nordenskjöld, Die krystallinische Gesteine der Magellansländer, *Svenska Exped. till Magellansländern*, Stockholm, 1901, vol. i., p. 175.

Analyses of Granites of the Adamellite and Granodiorite Types.

	I. Adamellite Abriachan.	II. Adamellite Rubislaw.	III. Adamellite Landsberg.	IV. Adamellite Shap.	V. Adamellite Aberlour.	VI. Adamellite Glen Fyne.	VII. Granodiorite Calaveras.	VIII. Granodiorite Nevada City.
SiO_2 -	71.25	69.01	68.97	68.55	68.01	66.6	68.65	66 65
Al_2O_3 -	18.03	17.74	14.80	16.21	17.34	17.4	16.34	16.15
Fe_2O_3 -	1.29	.97	3.29	2.26	3.66	1.1	.93	1.52
FeO -	.34	2.05	—	—	—	2.1	1.48	2.36
MgO -	.38	.48	1.15	1.04	.77	1.2	1.29	1.74
CaO -	2.61	1.05	3.82	2.40	2.06	2.2	3.07	4.53
Na_2O -	2.25	2.73	2.46	4.08	2.05	3.1	4.85	3.40
K_2O -	3.09	3.94	4.53	4.14	4.41	4.6	1.85	2.65
H_2O -	.82	1.18	0.70	not est.	.64	.9	.86	.90
TiO_2 -	—		—	not est.	.83	—	.28	.38
Other constit.	.13		—	.45	.48	—	.39	.29
	100.19	100.05	99.72	99.13	100.25	99.2	99.99	100.57

I. Adamellite, Abriachan, Loch Ness, Scotland (W. Mackie).
II. do. Rubislaw, Scotland (W. Mackie).
III. do. Landsberg, Vosges Mountains (Unger). Type established by Brögger.
IV. do. Shap (J. B. Cohen).
V. do. Ruthrie Granite, Aberlour, near Ben Rinnes, Strathspey.
VI. do. Allt na Lairige, Glen Fyne, near Garabal Hill (Teall).
VII. Granodiorite, Indian Valley, Calaveras County, California (W. F. Hillebrand).
VIII. do. Nevada City, California (W. Lindgren).

FIG. 76.

Hornblende-granite (granodiorite).

f. Felspar (chiefly plagioclase).

q. Quartz. *m*. Mica.

h. Hornblende, with granules of Epidote.

THE SYENITE[1] FAMILY.

This large family of intermediate rocks is characterized by the presence of one or more of the alkali-felspars (orthoclase, perthite, soda-orthoclase, anorthoclase, microcline), or of the felspathoids (nepheline, leucite, and sodalite), together with a subordi-

[1] The term *syenite* was used by Pliny to designate a rock occurring at Syene (Assouan), in Egypt. This rock is a hornblende-biotite-granite. Werner applied it to all granular igneous rocks containing dominant felspars with subordinate amphibole, pyroxene and other minerals, and without noticeable quartz.

nate soda-lime-felspar, and one or more of the following ferro-magnesian constituents: amphibole (hornblende, arfvedsonite, barkevikite), pyroxene (augite, ægirine), and mica (biotite, lepidomelane, etc.). Rarer types are characterized by the presence of cancrinite, zircon, eudialyte, katapleiite, or melanite. Among accessory minerals, sphene, apatite, zircon, and the usual iron-ores (magnetite, ilmenite, and hæmatite), deserve especial mention. A rarer accessory is perovskite.

The typical structure of the syenites is the *granitic*. When quartz is present it occasionally occurs in micrographic intergrowth with orthoclase. The nepheline-syenites show a tendency to the development of the porphyritic structure, with large phenocrysts of nepheline.

The Potash-Syenite Sub-Family.

The original type selected by Werner for the syenites is the orthoclase-hornblende-rock of Plauen, near Dresden. Werner's object was to establish a type of felspathic igneous rock having a granitic structure, but distinguished from granite by the absence of noticeable quartz. The rock of Syene (Assouan), in Egypt, from which Pliny derived the word syenite, contains quartz, and is in fact a hornblende-biotite-granite. The Plauen rock (*plauenite* of Brögger), on account of its dominant hornblende, may be conveniently termed a hornblende-syenite, and the terms augite- or biotite-syenite may be used for syenites characterized by the combination orthoclase-augite and orthoclase-biotite.

In these rocks there is always present, in sub-

ordination to orthoclase, a member of the soda-lime series (oligoclase or andesine). Quartz is not entirely absent, as the microscopic examination of thin sections shows. By the increase in this mineral the rocks pass through quartz-syenite into potash-granite. The dark-coloured minerals are often present in considerable quantity, and then impart a dark tint to the rock. The hornblende, which, with rare exceptions, is a green variety, may be recognized by its pronounced pleochroism, its well-marked cleavage, its prism angle

Analyses of Potash-Syenites.

	I. Reichenstein.	II. Plauen.	III. Biella.	Average.
SiO_2	62·51	59·83	59·37	60·57
Al_2O_3	12·78	16·85	17·92	15·85
Fe_2O_3	2·56	—	6·77	8·23
FeO	4·76	7.01	2·02	—
MgO	3·33	2.61	1·83	2·59
CaO	4·76	4.43	4·16	4·44
Na_2O	2·71	2·44	1·24	2·13
K_2O	4·81	6·57	6·68	6·02
H_2O	1·53	1·29	0·38	1·06
TiO_2	0·81	—	0·26	0·53
P_2O_5	—	—	0·58	(0·58)
	100·56	101·03	101·21	

I. Augite-syenite, Reichenstein, Silesia. Traube: *Neues Jahrbuch*, 1890., I., p. 206.

II. Hornblende-syenite, Plauen, near Dresden. F. Zirkel: *Pogg. Ann. B.*, 122, 1864, p. 622.

III. Hornblende-syenite, Biella, Piedmont. Cossa: *Mem. Acad. d. Sc. di Torino.* (2) B. VIII., p. 28.

of 124°, its small extinction angle, etc. The augite is more variable in character: sometimes it is almost colourless or pale-green; at other times it partakes more of the nature of diallage, having then a violet-brown tint. The mica is always a brown biotite. It is very liable to chloritization, turning green in the first stage of the process. Muscovite is never present except as a secondary constituent.

The foregoing analyses of typical potash-syenites were selected by Brögger[1] for the calculation of the average composition of potash-syenites.

The Soda-Syenite Sub-Family.

In the soda-syenites the dominant felspar is either soda-orthoclase or anorthoclase, although albite and orthoclase may also be present without being intergrown to form perthite. The pyroxenes and amphiboles are represented by the soda-silicates—ægirine, arfvedsonite, barkevikite, riebeckite, etc. In consequence of the subordination of dark-coloured minerals the soda-syenites have in general a lighter colour than the potash-syenites. They grade by increasing quartz into the soda-granites, and by the appearance and increase of nepheline into nepheline-syenites.

The following are the chief types:—

Pulaskite.—This type was first described by J. F. Williams[2] from the Fourche Mountains in Arkansas as consisting essentially of a soda-orthoclase (micro-

[1] Die Triadische Eruptionsfolge bei Predazzo. *Vidensk. Skrifter I. Math.-natur. Klasse*, 1895, No. 7, p. 31.

[2] J. F. Williams: The Igneous Rocks of Arkansas. *Ann. Rep. Geol. Survey of Arkansas*, 1890, p. 74.

perthite) together with biotite and a brown or green hornblende (barkevikite or arfvedsonite). Plagioclase and quartz are, as a rule, absent. The occasional presence of nepheline and sodalite indicates a passage to the nepheline-syenites.

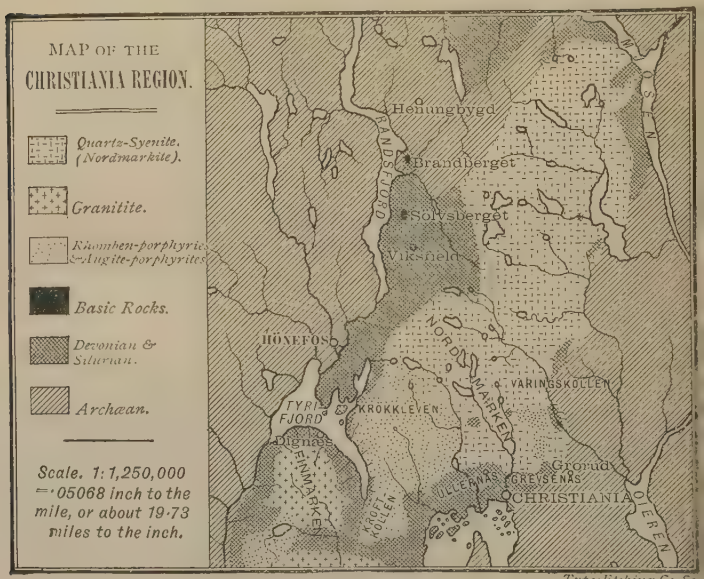

FIG. 77.

Map of the Christiania District, showing the distribution of the Nordmarkite and other members of that petrographical province. (In reproducing this map from the *Quart. Journ. of the Geol. Soc.* (vol. l., 1894, p. 16), I have at Prof. Brögger's request interchanged the references to the Nordmarkite and the Granitite, which had been incorrectly given.)

Closely related to pulaskite is the **nordmarkite** type, described by Brögger[1] as covering a large area

[1] Brögger: Die post-silurischen Eruptivgesteine des Christiania-gebietes. *Zeitsch. für Kryst.*, vol. xvi., 1890, p. 55.

in the Christiania district, except that it contains quartz, and thus constitutes a passage to the soda-granites. The felspar is a red microperthitic orthoclase, veined with albite. Some oligoclase is also present; and the coloured minerals, which are present in subordinate quantity, consist of ægirine and arfvedsonite.

The **Laurvikite**[1] type of Brögger[2] is characterized chiefly by its rhomb-shaped felspars, which consist of cryptoperthite or anorthoclase, or of both. Plagioclase is absent. The coloured minerals comprise green ægirine, hornblende (barkevikite) and biotite (lepidomelane). Accessory constituents are olivine, apatite and zircon, and occasionally a little nepheline and sodalite.

Rosenbusch[3] proposes to embrace the alkali-amphibole syenites under the name **Umptekite**, which was given by Ramsay[4] to a type occurring on the margin of the nepheline-syenite *massif* of the Kola Peninsula.

The **Åkerite** type, described by Brögger[5] from Aker in the Christiania district, is a quartz-bearing augite-syenite which, besides alkali-felspar (a perthitic orthoclase), contains much plagioclase, and is therefore closely allied to the monzonite family (see p. 183). The augite of this rock is a green idiomorphic diopsied.

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[1] Name derived from Laurvik in Southern Norway.

[2] Brögger: *Zeitsch. für Kryst.*, vol. xvi., 1890, p. 30.

[3] *Mikroskopische Physiographie*, 1907, p. 151.

[4] Ramsay: *Fennia* II. No. 2. Helsingfors, 1894.

[5] Brögger: *loc. cit.*, p. 45.

The soda-syenites may also be classified according to their pyroxenes and amphiboles into *riebeckite-syenite, arfvedsonite-syenite, ægirine-syenite*, etc.

The following are analyses of the chief types:

ANALYSES OF SODA-SYENITES.

	I. Nordmarkite	II. Umptekite.	III. Pulaskite.	IV. Laurvikite.	V. Akerite.
SiO_2	64·04	63·71	60·03	56 85	5 ·79
Al_2O_3	17·92	16·59	20·76	21·56	16·64
Fe_2O_3	0·96	2·92	4·01	3·44	9·58
FeO	2·08	0·66	0·75	1·14	
MgO	0·59	0·90	0·80	0·85	2·63
CaO	1·00	3·11	2·62	5·26	5 12
Na_2O	6·67	8·26	5·96	6·07	5·30
K_2O	6·08	2·79	5·48	3·66	2·55
H_2O	1·18	0·19	0·59	0·52	1·27
TiO_2	0·62	0·86	—	—	—
Other constits.	·23	0·20	0·07	—	—
	101·37	100·19	101·07	99·35	99·88

I. Nordmarkite, Tonsenås, Christiania.—P. Janasch, quoted by Brögger: *Zeitsch. für Kryst.*, vol. xvi., 1890, p. 54.

II. Umptekite, Umpjaur, Kola Peninsula, quoted from Rosenbusch: *Gesteinslehre*, p. 112.

III. Pulaskite, Fourche Mts., Arkansas, *ibid.*

IV. Laurvikite, red variety, Nötterö, Christiania.—G. Forsberg in Brögger: *Zeitsch. für Kryst.*, vol. xvi., 1890, p. 30.

V. Akerite, Vettakollen, near Christiania.—Th. Kjerulf, quoted by Brögger: Die Triadische Eruptionsfolge bei Predazzo, *Vidensk. Skrifter I.*, 1895, No. 7, p. 33.

THE FELSPATHOID-SYENITE SUB-FAMILY.

We come now to the consideration of the important division of the syenite family which in addition to an

alkali-felspar (orthoclase, microcline, micro-perthite, soda-orthoclase, or albite) contains one or more of the felspathoid minerals (nepheline, leucite, sodalite, etc).

The pyroxenes and amphiboles are of great variety, and occur either independently or intergrown. Among the former, diopside, ægirine-augite and ægirine (acmite), and among the latter, brownish-green hornblende, barkevikite, arfvedsonite, and hastingsite are known; while the biotite is usually the variety known as lepidomelane. The members of this sub-family are usually classified according to the nature of the felspathoid constituent into nepheline-syenite, leucite-syenite, sodalite-syenite, etc.

Nepheline-Syenite.—A great number of types of nepheline-syenite have been distinguished. Of these the most widely distributed is the Foya type (*foyaite*),[1] which was first described by Blum from the Foya Hills, in the Serra de Monchique of Southern Portugal. In this type potash-felspar (orthoclase) and nepheline are present in approximately equal proportions, while the coloured minerals are subordinate. According as the latter are represented by hornblende, augite, or biotite, the varieties *hornblende-foyaite*, *augite-foyaite* and *biotite-foyaite* can be distinguished.

In some nepheline-syenites, a soda-felspar accompanies the potash mineral. Thus *litchfieldite* is the

[1] It should be noted that Brögger (*Zeitsch. für Kryst.*, vol. xvi., 1890, p. 39) has adopted the term *foyaite* for nepheline-syenites having a trachytic structure (*i.e.* with tabular felspars in parallel arrangement) in contradistinction to *ditroite*, which he uses for those having a granitic structure.

name given by Bayley [1] to a type in which orthoclase is subordinate to albite; and in the *mariupolite* of Morozewicz [2] albite is alone present.

Ditroite (from Ditró in Transylvania) is a type characterized by abundant sodalite and subordinate coloured minerals (chiefly biotite, seldom augite). In *miaskite* (so named by G. Rose from Miask in the Ilmen Mountains of Russia) both sodalite and cancrinite are present, and biotite is abundant.

The *laurdalite* of Brögger [3] is a characteristic type developed typically at Laurdal in Southern Norway. It is a coarse-grained rock containing both nepheline and sodalite, the former often in large phenocrysts. The felspar, which may be either a soda-orthoclase (cryptoperthite) or a soda-microcline (anorthoclase), occurs in rhomb-shaped crystals, a character which allies laurdalite to laurvikite. Olivine is an accessory constituent.

Eudialyte-syenite, a rock consisting of alkali-felspars, nepheline, ægirine and eudialyte, has been described by W. Ramsay from the Kola Peninsula. The *katapleiite-syenite* of Törnebohm [4] contains, besides alkali-felspars, nepheline and ægirine, eudialyte and katapleiite. *Cancrinite-syenite*, also described by Törnebohm, consists of albite, a little orthoclase, nepheline, ægirine and cancrinite.

All the types of nepheline-syenite described above contain felspar in greater or less quantity. There

[1] *Bull. Geol. Soc. America*, 1882, III., p. 231.
[2] *Tscherm. Min. u. Pet. Mitt.*, vol. xxi. (1902), p. 238.
[3] *Zeitsch. für Kryst.*, vol. xvi. 1890, p. 32.
[4] *Sveriges Geol. Undersökningar*, 1906.

exists, however, a type in which the felspathic constituent is absent, the rock then consisting solely of nepheline with a ferromagnesian constituent. Thus Ramsay[1] has described as *urtite* a type which consists solely of nepheline and ægirine, and Adams[2] has described as *monmouthite* a similar rock, consisting essentially of nepheline and black hornblende, which occurs in the township of Monmouth in Ontario.

Leucite-syenite. — The leucite-syenites are far less abundant than the nepheline-syenites. The first example of this rock was described by J. F. Williams[3] from Magnet Cove in Arkansas. The rock consists of porphyritic crystals of pseudo-leucite in a groundmass of nepheline, orthoclase and melanite. A similar rock was described by Hussak[4] from Serra dos Poços de Caldas in Brazil.

Sodalite-syenite. A type of syenite in which sodalite predominates has been described by Ramsay from the Kola Peninsula as *tawite*. It is composed of sodalite and ægirine. A type consisting solely of sodalite appears to exist in Greenland. It may be described as *sodalite-rock*.[5]

The average chemical composition of the nepheline-syenites has been calculated by Brögger[6] from thirteen

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[1] *Geol. Fören. i. Stockh. Förh.*, vol. xviii. (1896), p. 459.

[2] *Amer. Journ. of Sci.*, vol. xvii. (1904), p. 269.

[3] *Ann. Rep. Geol. Surv. Arkansas*, for 1890 and 1891.

[4] *Neues Jahrb.*, 1892, ii. p. 146.

[5] Rosenbusch: *Mikroskopische Physiographie*, 1907, p. 240.

[6] Brögger: Die Eruptionsfolge der Triadischen Eruptivgesteine bei Predazzo in Südtyrol. *Vidensk. Skrifter I.*, 1895, No. 7, p. 29.

ANALYSES OF NEPHELINE-SYENITES.

	I. Nepheline-syenite Litchfield.	II. Nepheline-syenite Norway.	III. Nepheline-syenite Ditró.	IV. Foyaite Serra de Monchique.	V. Foyaite Transvaal.	VI. Laurdalite Norway.
SiO_2	60.39	56.71	56.30	54.20	53.73	51.90
TiO_2	—	—	—	1.04	0.09	—
Al_2O_3	22.57	22.49	24.10	21.74	20.35	22.54
Fe_2O_3	0.42	3.40	1.99	0.46	3.74	4.03
FeO	2.26			2.36	2.13	3.15
MgO	0.13	1.19	0.13	0.52	0.47	1.97
CaO	0.32	2.22	0.69	1.95	2.72	3.11
Na_2O	8.44	7.37	9.28	8.69	7.94	8.18
K_2O	4.77	5.87	6.79	6.97	6.05	4.72
H_2O	0.57	0.45	1.58	2.32	2.02	0.22
Other constits.	0.08	—	—	—	0.23	—
	99.95	99.70	100.86	100.25	99.47	99.82

I. Nepheline-syenite (Litchfieldite), Litchfield, Maine, U.S. (L. G. Eakins).
II. do. Bratholmen, Landgangsfjord (G. Forsberg).
III. do. (Ditroite), Ditró, Siebenburgen (Fellner).
IV. do. (Foyaite), Serra de Monchique, Portugal (P. Tannasch).
V. do. do. Zwartkoppie Range, near Rustenburg (Wülfing).
VI. do. (Laurdalite), Lunde im Lougenthal (G. Forsberg).

analyses of typical occurrences to be $SiO_2 = 55{\cdot}78$, $TiO_2 = 0{\cdot}55$, $Al_2O_3 = 21{\cdot}34$, $Fe_2O_3 = 5{\cdot}35$, $MgO = 0{\cdot}78$, $CaO = 1{\cdot}93$, $Na_2O = 7{\cdot}82$, $K_2O = 5{\cdot}83$, $H_2O = 1{\cdot}29$. Ratio of the bases $CaO : Na_2O : K_2O = 1 : 4 : 2$.

The analyses given in the table on p. 182 are of well-known types.

THE MONZONITE FAMILY.

Occupying a middle position in the Intermediate Group between the syenites and the diorites are the **monzonites**;[1] that is to say they are rocks in which

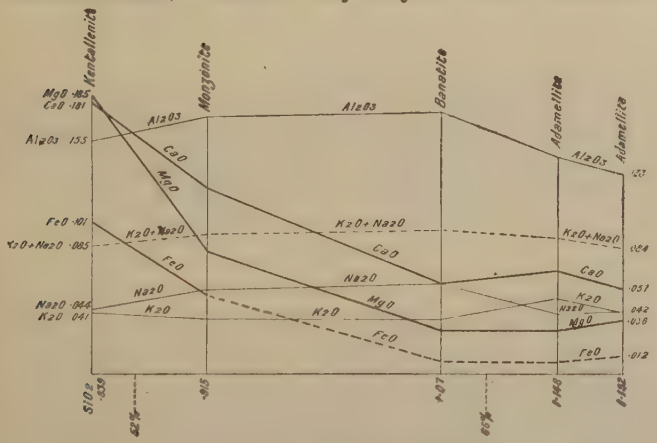

FIG. 78.

Diagram showing the relation of rocks of the Monzonite Series.

[1] This name was given by de Lapparent in 1864 to the rocks of Monzoni in the Tyrol (*Ann. d. Mines.* (6), vi., 1864, p. 259), and has been used with varying significance by different authors. It is used here in the sense defined by Brögger: "Das wirklich charakterische bei diesen Gesteinen ist dass sie in der Regel Orthoklas und Plagioklas führen ungefähr gleich reichlich, oder jedenfalls beide reichlich führen." Die Triadische Eruptionsfolge bei Predazzo, *loc. cit.* p. 21.

the soda-lime felspars (plagioclase) play a greater rôle than in the syenites, but not so great as in the diorites. Since the two kinds of felspar may be associated in every proportion, it is necessary to adopt some arbitrary dividing lines between the monzonites and the syenites on the one side, and between the monzonites and the diorites on the other. The suggestion made by Lindgren[1] is adopted here, namely, that rocks having alkali-felspar to the extent of more than two-thirds of the total felspar are classed with the syenites, and those with less than one-third with the diorites. Consequently the monzonites embrace all those intermediate plutonic rocks in which the ratio of alkali-felspar to soda-lime felspar is less than two-thirds and more than one-third.

With regard to silica—the monzonites have a percentage range between 52 and 66. With more than 66 per cent. they pass into the adamellite division of the granites, and with less than 52 per cent., into olivine rocks of the kentallenite type.[2] The most acid division of the family, corresponding to the tonalites in the diorite family and to the quartz-syenites in the syenite family, are the *banatites*. The range of silica in this sub-division is fixed by Brögger at between 63 and 66 per cent.

The monzonites are characterized by a fairly high percentage of alumina, which averages about 17 per

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[1] *Amer. Journ. of Sci.*, vol. ix., 1900, p. 269.

[2] Brögger: Die Triadische Eruptionsfolge bei Predazzo, *loc. cit.*, p. 61.

cent.; lime is from 6 to 8 per cent.; while potash and soda are present in roughly equal percentages. The soda-lime felspar may vary from andesine to labradorite. Quartz is absent, or present only in small quantities in the most acid members (the banatites). The dark minerals—pyroxene (both augite and hy-

FIG. 79.

Monzonite, Monzoni, Tyrol.
(Between crossed nicols.)

Or.	Orthoclase.	*Pl.*	Plagioclase.
P.	Pyroxene.	*H.*	Hornblende.
O.	Quartz.	*B.*	Biotite.

(After Brögger.)

persthene), hornblende and biotite, are variable in quantity, but always sufficiently developed to determine a dark colouration of the rock. Nepheline and leucite occur occasionally, thus affording a passage to the nepheline-syenites. Olivine only appears in the

more basic members of the family. Accessory minerals are sphene, zircon, apatite, and the usual iron-ores. The mean chemical composition, as calculated by Brögger from a number of analyses of typical monzonites, is given in the following table:

ANALYSES OF MONZONITES.

	I. Banatite Charnwood Forest.	II. Monzonite Stratherric.	III. Monzonite Monzoni.	IV. Monzonite Brögger's Average.
SiO_2	64·30	59·34	54·20	54·90
Al_2O_3	17·89	18·91	15·73	17·44
Fe_2O_3	4·75	6·22	3·67	9·64
FeO	—	·95	5·40	—
MgO	1·12	2·55	3·40	3·26
CaO	3·33	3·97	8·50	6·96
Na_2O	3·84	2·61	3·07	3·50
K_2O	3·37	2·91	4·42	3·51
H_2O	1·60	1·43	0·50	1·23
TiO_2	—	·72	0·40	·71
Other constits.	—	·39	1·21	—
	100 20	100·00	100·50	—

I. Banatite, Croft Hill, Charnwood Forest. (E. E. Berry).

II. Monzonite, Stratherric, Glen Liath, Inverness-shire (W. Mackie, *Trans. Geol. Soc. Edin.*, vol. viii., 1905, p. 54.)

III. Monzonite, Monzoni, Tyrol. (M. Schmelck).

IV. Brögger's average of fourteen typical Monzonites. Die Triadische Eruptionsfolge bei Predazzo, *loc. cit.*, p. 63.

THE DIORITE FAMILY.

The diorite family is that division of the intermediate group of plutonic rocks in which soda-lime felspar

largely predominates over alkali-felspar. According to the rule we have adopted, the ratio of orthoclase to plagioclase must not exceed one-third to two-thirds. The dominant felspar is a soda-lime felspar ranging from oligoclase to labradorite; but some orthoclase is notably present in all diorites.

With regard to silica, the limits are those of the intermediate group, namely 52 to 66 per cent. With more than 66 per cent. the diorites pass into the granodiorites, and with less than 52 per cent., into the gabbros. The more acid diorites contain a fair amount of quartz, and it is customary to distinguish these rocks as *quartz-diorites* or *tonalites*. The original Tonale type is a quartz-diorite containing abundant dark mica, together with hornblende. The tonalites are allied to the banatites, the difference between them consisting in the relative proportion of orthoclase and plagioclase. The most common ferromagnesian constituent in the diorites is green or brown hornblende,[1] in crystals or allotriomorphic grains; but brown biotite, pale green or colourless augite (salite or malacolite) and rhombic pyroxenes also occur.

Among accessory minerals the iron-ores (magnetite, ilmenite, pyrites), apatite, sphene and zircon are the most frequent. Secondary minerals are chlorite, epidote, limonite and calcite.

Typical diorites have a granitic structure, but with a texture less coarse than in the granites. Frequently

[1] The name diorite (Gr. διορίζω) was given by Haüy on account of the marked contrast between the hornblendic and the felspathic constituent. (*Traité de Min.*, 1822, p. 540.)

the grains are allotriomorphic and equi-dimensional. Occasionally, however, there is a tendency towards porphyritic structure, and then the plagioclase, and more rarely the hornblende, is idiomorphic. Orthoclase and quartz occur interstitially, with a tendency towards micrographic intergrowth.

Spheroidal structure, similar to that described when dealing with the granites, is well developed in the ball-diorite or *napoleonite* of Corsica, where the spheroids consist of hornblende and felspar, and show a well-developed radial and concentric arrangement.

A usual classification of the diorites based on the ferromagnesian minerals is:—*diorite* (=*hornblende-diorite*), *mica-diorite*, *augite-diorite* and *hypersthene-* or *enstatite-diorite*.

Some selected analyses of typical occurrences are given in the table on p. 189.

THE ALKALI-GABBRO FAMILY.

The family of the alkali-gabbros comprises plutonic rocks of granitic structure, with less than 52 per cent. of silica, and containing a considerable proportion of alkali-felspar. It includes basic representatives of the felspathoid, the potash, the soda and the monzonite series. These are distinguished here as the nepheline-gabbro, the shonkinite, the essexite, and the kentallenite sub-families, all of which are closely allied and grade into one another by variations in their felspathic and felspathoid elements.

Analyses of Diorites.

	I. Tonalite Carinthia.	II. Diorite, Brögger's average.	III. Diorite Dandaleith.	IV. Diorite Netherly.	V. Augite-diorite Minnesota.
SiO_2 - -	63.09	56.52	54.09	53.22	52.35
Al_2O_3 - -	18.89	16.31	16.72	16.84	15.72
Fe_2O_3 - -	3.48	4.28	—	—	2.90
FeO - -	2.02	5.92	9.38	9.27	7.32
MgO - -	1.97	4.32	5.58	6.48	7.36
CaO - -	6.18	6.94	8.35	8.53	8.98
Na_2O - -	3.14	3.43	1.23	3.54	2.81
K_2O - -	1.30	1.44	.97	1.39	1.32
H_2O - -	0.63	1.03	2.58	.95	1.35
TiO_2 - -	—	.25	—	—	—
Other constits.	—	.54	.96	—	—
	100.70	100.98	99.86	100.22	100.11

I. Tonalite, Wistra, Carinthia, Austria (W. Krezmar).
II. Brögger's average of 16 analyses of typical diorites : Die Triadische Eruptionsfolge bei Predazzo, *loc. cit.*, p. 36.
III. Diorite, Dandaleith, near Ben Rinnes, Strathspey, Scotland (W. Mackie).
IV. Diorite, Netherly, near Ben Rinnes, Strathspey (W. Mackie).
V. Augite-diorite, Little Falls, Minnesota (Streng and Kloos).

The Nepheline-Gabbro Sub-Family.

The nepheline-gabbro sub-family comprises basic plutonic rocks characterized by the presence of a considerable amount of nepheline (or other felspathoid) in combination with orthoclase or plagioclase, or with both. A large proportion of dark-coloured ferro-magnesian minerals determines a melanocratic character, and distinguishes them from the nepheline-syenites, into which they pass by an increase in the silica-content. The following types may be distinguished:—

Theralite = plagioclase (with or without orthoclase) + nepheline.

Covite = orthoclase + nepheline.

Borolanite = orthoclase + pseudo-leucite + nepheline + melanite.

To these may be added the felspar-free ijolite, jacupirangite and missourite:

Ijolite = nepheline + augite + melanite.

Jacupirangite = nepheline + augite + biotite + magnetite.

Missourite = leucite + augite + biotite + olivine.

Theralite.—This name was originally proposed by Rosenbusch for the plutonic representatives of the tephrites (volcanic plagioclase-nepheline rocks) before such rocks had in reality been discovered.

The type is of rather rare occurrence, but rocks closely corresponding to the definition have been discovered in the Cordilleras of Costa Rica.

The rock described as theralite by J. E. Wolff from the Crazy Mountains in Montana (Gordon's Butte)

must, on account of its dominant orthoclase-content, be referred to the covite type.

The theralite type may be briefly defined as a dark-coloured basic plutonic rock consisting essentially of nepheline in combination with a plagioclase of the

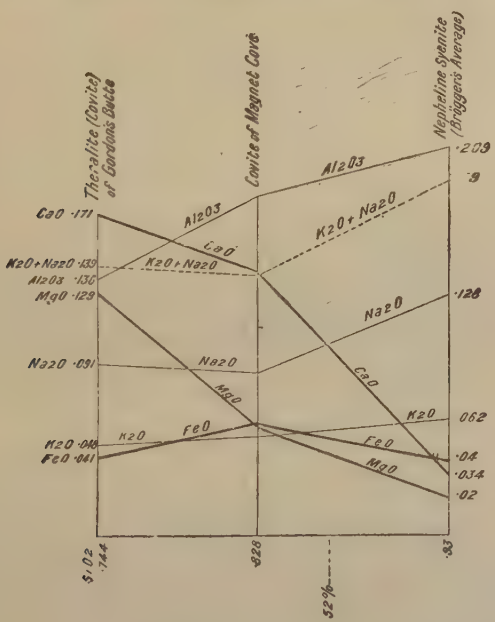

FIG. 80.

Diagram showing the relation of rocks of the Nepheline Series.

andesine-labradorite type and subordinate orthoclase. In addition, there are present augite, biotite, sodalite, olivine, magnetite and apatite. The augite is a greenish or violet-brown titaniferous variety.

Chemically the theralites are characterized by their high percentage of alkalies, lime, magnesia, and iron, in combination with low silica. They are intimately related to the essexites, differing only in the relative proportions of nepheline and felspar.

Covite.—This name has been proposed by H. S. Washington[1] for a holocrystalline combination of alkali-felspar (principally orthoclase) and nepheline with hornblende and ægirine-augite. The type rock occurs at Magnet Cove, Arkansas. It is of basic composition and granitic structure. In colour it is rather leucocratic than melanocratic, but since light and dark minerals are about equal in quantity Washington terms it "mesocratic." From an analysis of the type rock, the following mineral composition has been calculated: orthoclase, 29 per cent.; albite, 23 per cent.; nepheline, 9 per cent.; hornblende, 19 per cent.; augite, 13½ per cent.

With increasing silica the type passes into nepheline-syenite. By an increase in the proportions of soda-lime felspar and of nepheline it grades into theralite; while with decreasing nepheline it merges into the shonkinite type (as defined by Pirsson).[2]

Borolanite.—This name was given by Teall[3] to a peculiar type of basic plutonic rock occurring near Loch Borolan in Southern Assynt. The dominant

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[1] *Journ. of Geol.*, vol. ix., 1901, p. 612.

[2] Rosenbusch's definition of shonkinite differs from that of Pirsson in that nepheline is made an essential constituent. Thus defined shonkinite would include covite.

[3] *Trans. Roy. Soc. Edin.*, vol. xxxvii. (1892), p. 163.

constituents are orthoclase, pseudo-leucite, melanite, pyroxene, and biotite. Plagioclase and nepheline are subordinate. The typical rock is a granular aggregate of orthoclase and melanite containing polyhedral, light-coloured patches, which under the microscope are found to consist of a micrographic intergrowth of orthoclase and some zeolitic mineral, the whole being pseudomorphous after leucite. Nepheline and sodalite also occur as original constituents.

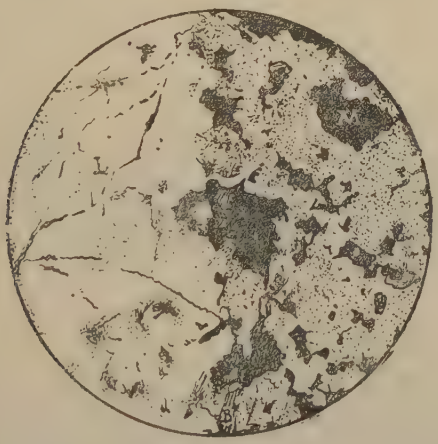

FIG. 81. Borolanite, Cnoc-na-Sroine, Borolan.

The light part (L.) is a portion of a phenocryst of pseudo-leucite, the remainder is groundmass composed of orthoclase, melanite (M.), and biotite (B.).

(*From a photograph by R. H. Rastall.*)

Chemically the borolanite type is allied to covite, the distinctive feature being the presence of pseudo-leucite and melanite in the former. Still more closely allied is the rock described by H. S. Wash-

ington as *arkite*;[1] but there is a difference in the relative proportions of orthoclase and nepheline, the latter being more, and the former less, abundant in the American rock. Washington defines arkite as " a holocrystalline, porphyritic, leucocratic combination of leucite (or pseudo-leucite) and nepheline, with pyroxene and garnet.". From a chemical analysis he calculates the mineral composition to be: orthoclase, 4 per cent.; leucite, 37 per cent.; nepheline, 25 per cent. Arkite constitutes a passage from borolanite to the felspar-free *missourite*,[2] in which there is leucite, but no orthoclase, and olivine is abundantly developed. In the allied *ijolite*[3] type nepheline composes 50 per cent. of the whole rock, the remainder being made up of augite and melanite.

Jacupirangite[4] is a type composed chiefly of augite, with a considerable amount of magnetite, and subordinate nepheline and biotite.

The Shonkinite Sub-Family.

The name **Shonkinite** was first given by Weed and Pirsson[5] to the dark rock of Square Butte in the Highwood Mountains of Montana—Shonkin being the Indian name of the Highwood range. The type as defined by these authors is "a granular, plutonic

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[1] *Journ. of Geol.*, vol. ix. (1901), p. 617. The name is derived from Arkansas.

[2] Pirsson, *Amer. Journ. of Sci.*, ii. (1896), p. 317.

[3] Ramsay and Berghell: *Geol. Fören. i. Stockh. Förh.*, vol. xiii. (1891), p. 300.

[4] Derby: *Amer. Journ. Sci.*, vol. xli., 1891, pp. 311 and 522.

[5] Pirsson: *Bull. Geol. Soc. Amer.*, vol. vi. (1895), pp. 389-422.

rock consisting of essential augite and orthoclase, and thereby related to the syenite family." The augite is a light green diopside variety. Other minerals are: hornblende (barkevikite), biotite, and olivine; nepheline, sodalite, iron-ores, etc., may be present in small quantities. The ferro-magnesian minerals generally make up about half of the rock constituents, thus imparting a melanocratic character to the rock.

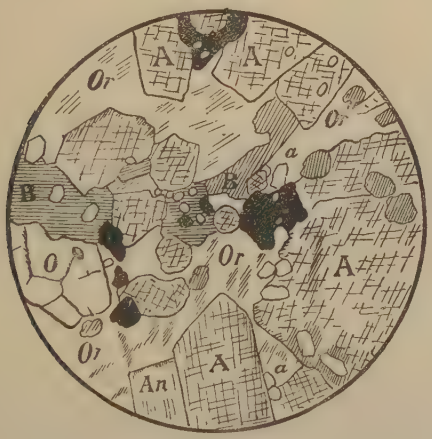

FIG. 82.

Shonkinite, the type rock of Square Butte.

Or.	Orthoclase.	*An.*	Anorthite.
A.	Augite.	*B.*	Biotite.
a.	do.	*O.*	Olivine.

(After Weed and Pirsson.)

The chemical composition of the shonkinites is rather peculiar. In conjunction with a low percentage of silica (46 to 48 per cent.) there is a high proportion of alkalies. The molecular pro-

portions of potash and soda are usually approximately equal. Lime and magnesia are very high. The shonkinites are thus at the basic end of the potash series, and grade with increasing silica into the potash-syenites. Their high proportion of potash separates them from the essexites, in which orthoclase is subordinate to an acid member of the soda-lime felspars, and soda is the dominant alkali. By the

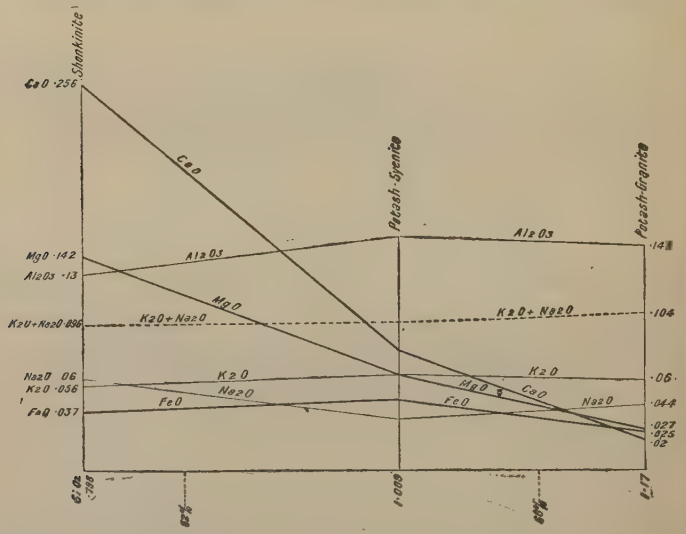

FIG. 83.

Diagram showing the relation of Shonkinite to the Potash Series.

addition of nepheline as a constituent the shonkinites pass into the covite type of nepheline-gabbro. On the other hand a shonkinite rich in olivine becomes a kentallenite by the addition of a sufficient proportion of lime-bearing felspar.

The Essexite Sub-Family.

The name **Essexite** was given by J. H. Sears[1] to a rock occurring in association with nepheline-syenites in Essex County (Salem Neck, near Boston), Massachusetts. It is a dark-coloured basic type closely related to the gabbros and to the kentallenites, but distinguished from these rocks by

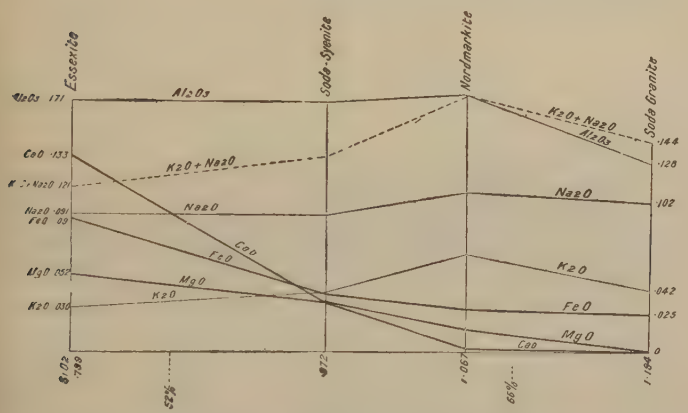

FIG. 84.

Diagram showing the relation of Essexite to the Soda Series.

a higher alkali-content, and by its association with nepheline-syenite and other rock types derived from a magma rich in soda. From the shonkinites it is separated by the higher proportion of soda as compared to potash. The proportion of lime is high, but a low magnesia-content is characteristic. Mineralogically

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[1] *Bull. Essex Institute*, vol. xxiii., 1891. See also Washington: *Journ. of Geol.*, vol. vii., 1899, p. 53.

the essexites consist essentially of a dominant calc-alkali felspar (oligoclase, andesine, labradorite) together with a variable quantity of orthoclase, nepheline, sodalite, augite, hornblende, biotite, and olivine. Apatite occurs, often in considerable quantity, as well as the usual iron-ores. The abundant deep-green, strongly pleochroic hornblende is, as a rule, a variety containing soda. The augite is mostly a green diopside, but a soda-pyroxene (ægirine-augite) also occurs. The structure is holocrystalline, but rather fine-grained, and there is a tendency towards the development of idiomorphic crystals, especially of hornblende and augite.

By an increase in the proportion of nepheline the essexites pass into the theralites.

Besides the type occurrence in New England, essexites have been described in the Monteregian Hills near Montreal (Mount Johnson),[1] from Rongstock in Bohemia, and from the Löwenburg in the Siebengebirge on the Rhine.

The Kentallenite Sub-Family.

The **Kentallenite**[2] type is the most basic member of the monzonite series; in fact it is identical with Brögger's olivine-monzonite. It may be defined as a basic plutonic rock with a coarse or medium-grained holocrystalline structure, and consisting essentially of augite, biotite, olivine, orthoclase and plagioclase. The two felspars are present

[1] Adams: *Journ. of Geol.*, vol. ii. (1903), p. 238.

[2] Hill and Kynaston: *Quart. Journ. Geol. Soc.*, vol. lvi. (1900), p. 531.

in roughly equal proportions. Apatite and magnetite are accessory. The felspars and the biotite form a matrix in which the olivine and augite are imbedded, these latter minerals showing a tendency to the development of idiomorphic contours. Under the microscope the augite is of a pale-green colour. The plagioclase ranges from oligoclase to labradorite. Chemically the rock is characterized by its high percentage of alkalies (potash and soda being roughly equal) and of lime and magnesia, combined

FIG. 85. Kentallenite, Kentallen.
Pl. Plagioclase. *A.* Augite. *O.* Olivine.
(*From a photograph by R. H. Rastall.*)

with a low percentage of silica. With increasing silica the kentallenites pass into the monzonites; with increasing potash (*i.e.* increasing orthoclase) into the shonkinites; and with increasing soda (by decrease in orthoclase and the addition of nepheline) into the essexites.

Analyses of Alkali-Gabbros.

	I. Shonkinite.	II. Essexite.	III. Kentallenite.	IV. Theralite.	V. Covite.	VI. Borolanite.
SiO_2	46.73	46.99	48.00	44.65	49.70	48.19
Al_2O_3	10.05	17.94	12.52	13.87	18.45	18.52
Fe_2O_3	3.53	2.56	8.74	6.06	3.39	4.51
FeO	8.20	7.56		2.94	4.32	1.68
MgO	9.68	3.22	15.26	5.15	2.32	1.12
CaO	13.22	7.85	7.94	9.57	7.91	10.29
Na_2O	1.81	6.35	3.11	5.67	5.33	3.44
K_2O	3.76	2.62	2.68	4.49	4.95	8.05
H_2O	1.24	.65	1.36	3.06	1.34	3.45
TiO_2	.78	2.92	.22	0.95	1.33	1.75
P_2O_5 and other constits.	1.93	.94	—	3.52	.40	—
	100.93	99.60	99.83	99.93	99.44	101.00

I. Shonkinite, Square Butte, Highwood Mts., Montana—L. V. Pirsson: *Bull. Geol. Soc. Amer.*, vol. vi., 1895, p. 389.

II. Essexite, Salem Neck, Essex County, Mass.—H. S. Washington: *Journ. of Geol.*, vol. vii., 1899, p. 57.

III. Kentallenite, Kentallen, near Ballachulish, Argyll—J. J. H. Teall: *Rep. Geol. Sur., 1896* [1897] p. 22.

IV. Theralite (Covite), Gordon's Butte, Crazy Mts., Montana—W. F. Hillebrand: *Bull. U. S. Geol. Sur.*, 1898, p. 201, quoted in Washington's Chemical Analyses, p. 347.

V. Covite, Magnet Cove, Arkansas—Washington: *Journ. Geol.*, ix., 1901, p. 612.

VI. Borolanite, Am Meallan, Loch Borolan, Ross—W. Campbell Smith, *personally communicated.*

THE GABBRO FAMILY.

This family comprises the basic members of the calc-alkali series of plutonic rocks; in other words, the gabbro are rocks of granitic habit with less than 52 per cent. of silica, and composed essentially of a lime-bearing plagioclase, together with one or more ferro-magnesian constituents.

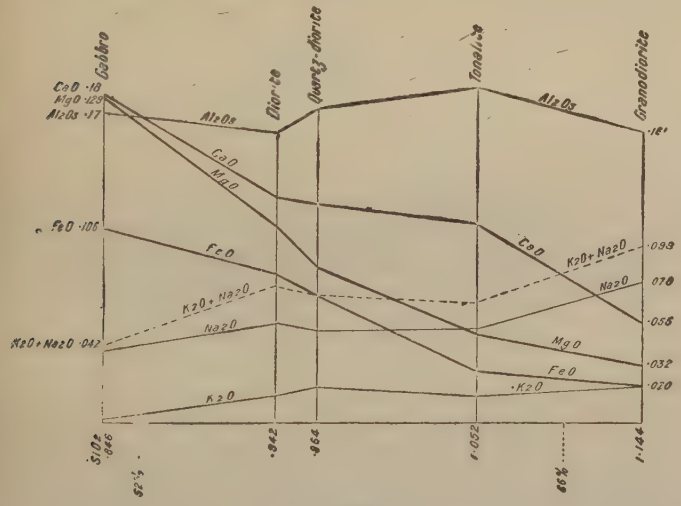

FIG. 86.

Diagram showing the relations of Gabbro to the Calc-alkali Series.

The word gabbro is derived from an Italian place-name, and originally signified a serpentine containing diallage. Von Buch first gave the type more precision by defining it as a rock composed essentially of plagioclase felspar and diallagic augite.[1]

[1] Haüy's *euphotide* (*Traité de Min.*, 1822, p. 535) was used in this sense.

The felspar is a basic plagioclase—generally labradorite, but occasionally bytownite or anorthite. Some oligoclase or andesine may be present in subordinate quantity. Orthoclase is absent except in rare instances, when it is associated with quartz in micrographic intergrowth.

Chemically the gabbros are characterized by high percentages of lime, magnesia, and ferrous oxide,

FIG. 87. Olivine-Gabbro, Sgurr nan Gillean, Cuillin Hills, Skye.

F. Plagioclase. *A.* Augite. *O.* Olivine.
(*From a photograph by R. H. Rastall.*)

together with low alkalies; potash is practically absent. There is a natural passage to diorites; and plagioclase-augite rocks with more than 52 per cent. silica may appropriately be termed augite-diorites. Rocks on the border line are sometimes termed gabbro-diorite or diorite-gabbro.

According to the nature of the ferro-magnesian constituents occurring in conjunction with the plagioclase, we may distinguish the following types:

Gabbro = labradorite + augite.
Olivine-gabbro = labradorite + augite + olivine.
Norite = labradorite + augite + hypersthene.
Olivine-norite = labradorite + augite + hypersthene + olivine.
Troctolite [1] = labradorite + olivine.
Eucrite = anorthite + augite + olivine.
Allivalite [2] = anorthite + olivine.
Anorthite-rock = anorthite alone.

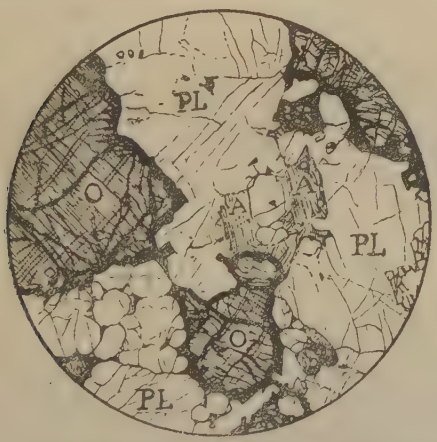

FIG. 88. Olivine-Gabbro, Sgurr nan Gillean, Cuillin Hills, Skye.
Pl. Plagioclase. *A.* Augite. *O.* Olivine.
(*From a photograph by R. H. Rastall.*)

[1] So named by von Lasaulx from its spotted appearance, due to the contrast of the dark olivine grains, which are full of magnetite, to the paler felspar crystals, (cf. the German name **Forellenstein**, *anglice*, troutstone).

[2] Harker: *Summary of Progress, Geol. Surv.*, 1903, p. 56. The name is derived from Allival, a mountain in the Isle of Rum.

By a diminution in the proportion of felspar and corresponding increase in the pyroxenic constituent, the gabbros pass into the pyroxenites ; and similarly if the olivine be increased at the expense of the felspar, they pass into the peridotites.

The felspar of the gabbros occurs in allotriomorphic, or in partially idiomorphic grains. It is twinned on the Carlsbad, albite and pericline types, often in combination. The well-marked albite twin-lamellation gives high extinction angles in properly oriented sections. When zonal structure is observed, the outermost zone is less basic than the interior, as shown by the variations in the extinction angles. Thus labradorite may be bordered by andesine. Though often perfectly fresh, the felspar is sometimes weathered into an opaque white substance known as saussurite, which can be resolved by microscopic examination into a confused and intimate aggregate of granules and fibres of zoisite, epidote and secondary felspar (albite), the last-named being of water-clear and glassy habit.

The augite is usually the variety known as malacolite. Besides the usual prismatic cleavage there is a pinacoidal parting, with which is associated a marked metallic or pearly lustre. Under the microscope, in sections oblique to this lamination, the fine striation characteristic of diallage is often apparent. The hypersthene is characterized by its pleochroism ; and by a marked coppery lustre, due to the reflection of light from numerous platy and rod-like inclusions arranged along parallel planes ("Schiller structure"). The hornblende, when an original con-

stituent, is sometimes a brown, sometimes a green variety. Secondary hornblende (actinolite, smaragdite, uralite), derived from the pyroxene, is also not uncommon, especially in those rocks that have suffered mechanical disturbance. Rocks in which the pyroxene is completely converted into hornblende may be appropriately termed uralitic gabbro. The term *epidio-*

FIG. 89. Allivalite, Allival, Rum.

Pl. Plagioclase (anorthite). *O.* Olivine.
(*From a photograph by R. H. Rastall.*

rite has been used in this sense, but it is not to be commended. The olivine occurs in idiomorphic grains, which, when fresh, are colourless. They are, however, often stained with limonite, and crowded with rods and granules of magnetite, which may become resorbed when the olivine is altered to serpentine.

Minerals accessory to the gabbros are dark mica, quartz, apatite, ilmenite, rutile and green and brown spinels (pleonaste, picotite, chromite).

In structure the gabbros are essentially holocrystalline and granitic, the constituent grains being allotriomorphic, although the felspars tend to be idiomorphic towards the augite. When this tendency is accentuated the ophitic structure is developed. In size the grains vary considerably, so that both coarse and fine textures occur. A finely granular or *granulitic* structure, in which the augites tend to show idiomorphic outlines, is developed in the so-called **pyroxene-granulite**,[1] which is the name given to certain gabbro-like rocks associated with crystalline schists occurring in Sutherland, in Saxony, in Madagascar, and in the United States. These rocks consist essentially of plagioclase felspar, hornblende, both monoclinic and rhombic pyroxene, and garnet; and are characterized by the freshness of the minerals, as well as by their typical (or "granulitic") structure.

The following table gives some analyses of typical gabbros.

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[1] Name given by Lehmann.

Analyses of Gabbros.

	I. Eucrite, Rum.	II. Olivine-gabbro, Sligachan.	III. Troctolite, Coverack.	IV. Allivalite, Rum.
SiO_2	48·05	46·39	45·73	42·20
Al_2O_3	15·35	26·34	22·10	17·56
Fe_2O_3	1·86	2·02	·71	1·20
FeO	7·53	3·15	3·51	6·33
MgO	12·53	4·82	11·46	20·38
CaO	11·02	15·29	9·26	9·61
Na_2O	1·26	1·63	2·54	1·11
K_2O	·19	·20	·34	·11
H_2O	·60	·58	4·38	1·19
TiO_2	·49	·26	—	·09
Other constits.	1·32	·14	—	·43
	100·20	100·82	100·03	100·21

I. Eucrite, three-quarters of a mile N.E. of summit of Allival, Isle of Rum. W. Pollard: *Summary of Progress, Geol. Surv.*, 1903, p. 56.

II. Olivine-Gabbro, Cuillin laccolith, west bank of Sligachan River, Skye. W. Pollard: *Summary of Progress, Geol. Surv.* 1899, p. 173.

III. Troctolite, Coverack, Cornwall. F. T. S. Houghton: *Geological Magazine*, 1879, p. 504.

IV. Allivalite, 70 yards south of summit of Allival, Rum. W. Pollard: *Summary of Progress, Geol. Surv.*, 1903, p. 56.

CHAPTER II

THE HYPABYSSAL ROCKS

The members of this class form a link connecting the volcanic with the plutonic rocks; but they are distinguished from the former by their *intrusive* character, and from the latter by the fact that they occur not as large intrusive masses, but as dykes, small sills, laccoliths, and small bosses, or as marginal portions of the plutonic masses themselves. They are further distinguished from the plutonic rocks by special micro-structures resulting from more rapid cooling; for, while the large, deep-seated, igneous masses, when typically developed, are characterized by the *eugranitic* structure, the hypabyssal rocks present structures that are more allied to those of the volcanic rocks. Thus the porphyritic structure, which is the result of consolidation in two phases, is frequently developed; a glassy base is not uncommon; and the spherulitic structure and those textures that result from differential movements prior to consolidation are also found. It will be seen that, speaking generally, the class has not the sharply-defined specific characters, such as distinguish the plutonic and the volcanic classes: on the contrary, its members are allied in mode of occurrence to the plutonic, but in micro-structure to the volcanic rocks.

Although the hypabyssal rocks do not constitute a large proportion of the igneous material of the earth's crust, in variety of type they surpass both of the other two classes. This is due to the fact that the class embraces rocks of two distinct modes of origin—namely, the undifferentiated and the differentiated. The *undifferentiated* hypabyssal rocks occur as apophyses, offshoots, or marginal portions of the larger plutonic masses; and have been produced by the consolidation of the same magma that formed the larger masses, but cooled under different conditions. On the whole they possess a similar chemical composition to the plutonic rocks with which they are associated. The *differentiated* hypabyssal rocks, on the other hand, have been produced by a splitting of the parent magma, in most cases before crystallization commenced, into secondary or partial magmas of different chemical composition. The process is considered to have been of the following nature:—First, a diffusion, towards the cooling surface, of the molecules rich in iron, magnesia, and lime caused a separation of the basic portion of the magma, which, under the influence of the pressure due to earth movements, furnished material for the intrusion of dykes, etc., of a basic, dark-coloured (*melanocratic*) type. The residual, more acid portion of the magma, provided the material for the intrusion of light-coloured (*leucocratic*) rocks. To express the relationship of the two types, thus differentiated from a common magma, Brögger [1] has proposed the term "*complementary*."

[1] *Quart. Journ. Geol. Soc.*, vol. 50, 1894, p. 31.

While the hypabyssal rocks of the undifferentiated type (*aschist* of Brögger) form a natural corollary to their related plutonic types, those of the differentiated type (*diaschist* of Brögger) constitute a sub-division of highly specialized rocks which can only be classified by reference to the parent magma from which they are derived.

The undifferentiated hypabyssal rocks may be sub-divided into five families :—

Hypabyssal Family.	*Corresponding Plutonic Family.*
1. The Quartz-porphyry Family.	Granite.
2. The Porphyry Family.	Syenite-Monzonite.
3. The Porphyrite Family.	Diorite.
4. The Dolerite Family.	Gabbro.
5. The Mugearite-Teschenite Family.	Alkali-gabbro.

Our knowledge of the differentiated hypabyssal rocks is, as yet, too incomplete to permit of a satisfactory classification. But in certain specific geological areas, the relations of the complementary differentiation products to their parent magmas appear to be clearly indicated. Thus the constant association of aplites with minettes in the neighbourhood of granitic intrusions makes it probable that these types are complementary differentiation products of a parent granitic magma. A like association of bostonites with camptonites in the neighbourhood of intrusions of alkali-gabbro (theralite or essexite), also indicates a complementary relation. For the present purpose it will suffice to divide the differentiated hypabyssal rocks into (1) a relatively acid or leucocratic group, and (2) a relatively basic or

melanocratic group, the members of which are complementary in Brögger's sense.

Group 1.—Leucocrates.

1. The Aplite Family.
2. The Pegmatite Family.
3. The Bostonite Family.
4. The Sölvsbergite-Tinguaite Family.

Group 2.—Melanocrates.

1. The Lamprophyre Family.
2. The Monchiquite-Alnöite Family.
3. The Picrite Family.
4. The Perknite Family.
5. The Peridotite Family.

The picrite, perknite, and peridotite families are treated here instead of with the basic plutonic rocks, with which they are often associated, because they are hypabyssal in their mode of occurrence: in other words, they occur either as dykes or as marginal modifications of plutonic masses, and there can be little doubt that magmatic differentiation has played an important part in their origin.

THE QUARTZ-PORPHYRY FAMILY.

This family comprises rocks that have the same general composition as granite, but occur, as smaller intrusions, namely, in bosses, dykes, or veins. In some cases they doubtless represent marginal modifications or apophyses of the main mass of granite with which they are associated. The family comprises granite-porphyry, microgranite, quartz-porphyry, granophyre, and pitchstone.

Granite-porphyry and **microgranite**. These two types are closely allied, both being composed of a granitoid but finely crystalline aggregate of quartz and felspar, together with a small amount of muscovite or some ferro-magnesian constituent; the distinction being the presence of phenocrysts of felspar, or of quartz, in the granite-porphyry. Small red garnets and fine needle-like prisms of dark tourmaline are frequent accessories. The rocks are generally of a light colour, varying from white to buff.

FIG. 90.

Granite-porphyry.
Crystals of Quartz and Felspar in a microcrystalline groundmass.
q. Quartz. *f*. Felspar.
(*After Fouqué and Lévy.*)

Under the general terms granite-porphyry and microgranite are included representatives of all the sub-divisions of the granite family: thus the soda-granite type is represented by *grorudite*, described by Brögger as a rock consisting of phenocrysts of microcline and ægirine in a holocrystalline groundmass of albite, microcline and ægirine, with abundant quartz.

Bosses and dykes of granite-porphyry and microgranite abound in the neighbourhood of granite, which they also penetrate. In the Cornish mining districts they are termed *elvans*.

Quartz-porphyry. This type consists of porphyritic crystals of quartz and felspar, or of quartz alone, imbedded in a cryptocrystalline or compact groundmass of the same minerals.

The quartz occurs sometimes in bi-pyramidal crystals, but oftener in rounded and corroded grains or blebs. The felspar (orthoclase) is frequently present in the form of large crystals, which, when the rock is decomposed, are often changed to an aggregate of kaolin, sericite, tourmaline, or chlorite. Ferro-magnesian minerals are subordinate, and are generally represented by a small quantity of brown mica, often more or less altered to chlorite. In the Cornish quartz-porphyries, schorl or black tourmaline is frequently present in isolated crystals or stellate groups.

The groundmass of the quartz-porphyries consists of a microcrystalline, micropœcilitic or cryptocrystalline aggregate of quartz and felspar. The cryptocrystalline structure is sometimes spoken of as *felsitic*.

The individual granules of which the so-called "felsitic matter" is composed, are so minute as scarcely to be recognizable even under high powers of magnification. Between crossed nicols a groundmass of this description has a characteristically dappled or flecked appearance, due to the transmission of light by innumerable minute particles of crystalline matter. Occasionally the groundmass is microcrystalline in the central part of a dyke, and cryptocrystalline or felsitic towards the margin. Rocks composed of felsitic material with few or no phenocrysts are often termed **felsites.**[1] Chemical examination of these rocks has shown that the felspathic constituent may be either a potash or a soda-felspar (albite or anorthoclase). Consequently the felsites may be classified as potash-felsites, soda-felsites (*keratophyres*), and potash-soda felsites.[2]

In another type micrographic and cryptographic intergrowths of the quartz and felspar occur, and when these are largely developed the rock is termed a **granophyre.**[3] In such rocks the felspar phenocrysts are often surrounded by a frame-work of micropegmatite, the felspathic element of which is in optical continuity with that of the phenocrysts.

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[1] Term introduced by Gerhard in 1814. Rosenbusch uses the expression *felsophyre* for these rocks.

[2] Hatch: *Geol. Mag.*, 1889, p. 545.

[3] The constant association of granophyre with gabbro, and the fact that the former is of later origin than the latter, suggests the possibility that in such cases the granophyre is an acid differentiation product of a gabbro magma. The term originated with Vogelsang, and was adopted by Rosenbusch in his scheme of classification.

By a radial arrangement of alternating lamellæ and fibres of quartz and felspar, beautiful spherulitic structures are developed.

Pitchstone.[1]—This name is applied to vitreous or semi-vitreous rocks, having the same chemical composition as granite, and produced by a rapid consolidation of an acid magma, when injected into fissures or between bedding planes. They are charac-

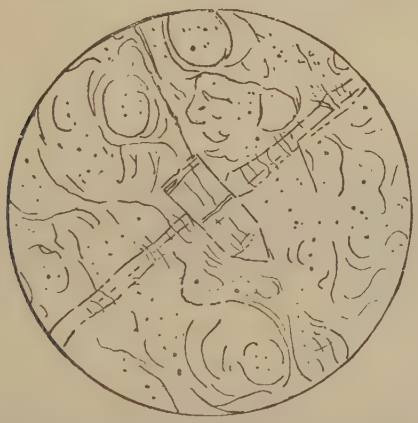

FIG. 91.

Pitchstone dyke, Eigg, under the microscope, showing Perlitic Structure. (*After Teall.*)

terized by a resinous appearance, conchoidal fracture, perlitic cracks, and flow structure. The colour is usually a dark green, more rarely black or red. Under the microscope the glass is seen to contain numerous crystallites and microlites, often arranged in beautiful stellate and feathery groups, or resem-

[1] *Vitrophyre* of Rosenbusch.

bling fern-growths. The larger crystallites occur as minute rods (microlites) of a greenish colour. They probably consist of hornblende since they give low extinction angles and show some degree of pleochroism.[1] (See Fig. 92.) Spherulitic structures are not infrequent.[2] Embedded in the glassy groundmass are isolated phenocrysts of quartz, orthoclase, mica, hornblende or augite.

FIG. 92.

Pitchstone of Arran, under the microscope, showing minute microlites of hornblende aggregated to feathery forms, in a glassy base.

(*After Teall.*)

With regard to chemical composition, the pitchstones differ from the granites, microgranites and

[1] Harker : *Mem. Geol. Surv., Sheet 21, Scotland*, 1903, p. 121.

[2] Many of the *Pyromerides* (Haüy, 1814) of the French, or *Kugelporphyre* of the Germans, are spherulitic rocks of this type.

Analyses of Acid Hypabyssal Rocks.

	I. Soda-felsite Arran.	II. Potash-soda-felsite Waterford.	III. Pitchstone Arran.	IV. Soda-felsite Knockmahon.	V. Granophyre Skye.	VI. Potash-felsite Great Newton Head.
SiO_2 - -	78.02	75.6	72.6	72.33	71.98	71.0
Al_2O_3 - -	11.46	12.8	12.4	8.97	13.13	14.2
Fe_2O_3 - -	—	—	.7	6.40	1.33	.8
FeO - -	1.61	1.9	1.1	1.06	1.64	.7
MgO - -	tr.	.4	tr.	tr.	0.56	1.1
CaO - -	0.13	.1	.9	1.98	1.15	tr.
Na_2O - -	7.72	3.0	1.7	5.83	2.98	.7
K_2O - -	0.20	5.6	4.7	1.46	4.93	9.6
H_2O - -	1.47	.5	5.2	1.86	1.77	1.5
TiO_2 - -	—	—	—	—	.37	—
Other constits.	—	—	—	—	.34	—
	100.61	99.9	99.3	99.89	100.18	99.6

I. Soda-Felsite, Corriegills, Arran (J. A. Phillips).
II. Potash-soda-Felsite, a boulder near Annestown, Waterford Coast (J. H. Player).
III. Pitchstone, Arran (J. H. Player).
IV. Soda-Felsite, dyke, Knockmahon, Waterford Coast (J. A. Phillips).
V. Hornblende-Granophyre, Beinn a' Chairn, 3½ miles S.-W. of Broadford, Skye (W. Pollard).
VI. Potash-Felsite, Great Newtown Head, Waterford (J. H. Player).

obsidians only by containing some 6 to 8 per cent. of water. By processes of devitrification they assume a stony or felsitic character (*felsitic pitchstones*); and it is probable that many of the compact flinty felsites have been produced from pitchstones by subsequent alteration.

The chemical composition of some typical British quartz-porphyries, etc., is shown in the table on p. 217.

THE PORPHYRY FAMILY.

This family includes hypabyssal equivalents of the syenites, nepheline-syenites and monzonites, on the one hand, and of the phonolites and trachytes on the other. The various types may be distinguished by reference to the plutonic rocks with which they are allied, *e.g.*, **syenite-porphyry**, **nepheline-syenite-porphyry**, **monzonite-porphyry**, or by reference to the nature of the phenocrysts, *e.g.*, **felspar-porphyry (orthophyre)**, **nepheline-porphyry**, etc. In the monzonite-porphyries, plagioclase is associated with orthoclase among the phenocrysts. The porphyries are all of intermediate chemical composition, and quartz rarely occurs in the form of phenocrysts, although it is often present to a small extent in the groundmass between the felspar prisms. When it is associated with the felspar in the form of micropegmatite, a type allied to the more acid granophyres is developed; and transitional forms between acid granophyres and granophyric porphyries of intermediate composition no doubt exist.

THE PORPHYRITE[1] FAMILY.

This family embraces the hypabyssal equivalents of the plutonic diorites on the one hand, and of the volcanic andesites on the other. The porphyrites occur as dykes, sills, and small laccoliths. The dominant porphyritic constituent is a lime-bearing plagioclase felspar. Ferro-magnesian minerals (augite, hypersthene, hornblende or biotite, occur either as phenocrysts or as constituents of the groundmass. The latter consists chiefly of felspar prisms with the occasional addition of interstitial quartz. Interstitial quartz occurs also intergrown with felspar as micropegmatite, in a granophyric type. The granophyric porphyrites, or dioritic granophyres, as they may be also termed since they are not markedly porphyritic, constitute a passage between the true granophyres and the dolerites. The rock of Markfield in the Charnwood Forest, or that of Penmaenmawr, which is classed by some as a hypersthene-diorite and by others as a hypersthene-dolerite, may be taken as a type of these rocks.[2]

The chemical composition of some typical British porphyrites is shown in the table on p. 220.

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[1] The former use of the word "porphyrite" for altered andesitic lavas, has been definitely abandoned in this country. As now used the distinction lies in the *intrusive* character of the porphyrites as opposed to the *extrusive* nature of the andesites.

[2] Since a specific name is desirable, that of *markfieldite*, from the Charnwood Forest occurrence, will be used for this type in this book.

Analyses of Porphyrites.

	I. Porphyrite Assynt.	II. Porphyrite Newlyn.	III. Dioritic Granophyre Penmaenmawr.	IV. Dioritic Granophyre Markfield.	V. Porphyrite Abercastle.
SiO_2 - -	63.41	59.84	58.45	55.7	55.38
Al_2O_3 - -	16.92	15.71	17.08	17.5	18.34
Fe_2O_3 - -	2.67	1.68	0.76	5.2	1.13
FeO - -	2.96	7.03	4.61	4.7	5.86
MgO - -	2.08	1.37	5.15	2.9	3.47
CaO - -	4.32	3.71	7.60	6.7	3.25
Na_2O - -	5.18	6.52	4.25	2.4	7.12
K_2O - -	2.36	2.76	1.02	2.1	0.22
H_2O - -	.64	.45	1.07	2.3	2.87
TiO_2 - -	—	.64	—	—	0.90
Other constits.	—	.42	—	—	CO_2 2.00
	100.54	100.13	99.99	99.5	100.54

I. Hornblende-porphyrite, base of Beinn an Fhurian, Assynt (Teall).
II. Augite-porphyrite, Gwavas Quarry, near Newlyn, Cornwall (W. Pollard).
III. Dioritic Granophyre or Markfieldite, Penmaenmawr, N. Wales (J. A. Phillips).
IV. Dioritic Granophyre or Markfieldite, Markfield, Charnwood Forest (J. H. Player).
V. Oligoclase-porphyrite, Abercastle, South Wales (J. V. Elsden).

THE DOLERITE FAMILY.

The **dolerites**[1] are dark-coloured rocks occurring in the form of small intrusive bosses, small laccoliths, sills and dykes. They are essentially holocrystalline aggregates of plagioclase and monoclinic augite; but various mineralogical types are furnished by the additional associations of a rhombic pyroxene, hornblende, mica, olivine or quartz, as for example—**hypersthene-dolerite, hornblende-dolerite, mica-dolerite, olivine-dolerite, quartz-dolerite.** A variety consisting almost entirely of plagioclase has been termed **leucophyre.** Many dolerites have a green colour due to the presence of a member of the chlorite family, which is developed at the expense of the augite. Hence the name *greenstone*,[2] which is still retained as a useful field-term without regard to composition. The term *diabase*[3] has been used instead of dolerite; but its use is not to be commended, since in Germany it has been applied to the more altered (chloritized) types, including those of volcanic origin.

[1] This name was introduced by Haüy in 1822. *Traité de Min.*, p. 573.

[2] De la Beche, in his "Report on the geology of Cornwall, Devon and West Somerset" (p. 27), defines "greenstone" as a combination of hornblende and felspar. Microscopic examination showed, however, that the ferro-magnesian constituent of these rocks is essentially augite, the hornblende being mainly of secondary origin.

[3] This word was introduced in 1813 by Alexandre Brongniart for rocks composed of felspar and hornblende; but the same mineral association was often designated by Haüy's term, diorite. The term was revived by Hausmann in 1842, who applied it to rocks composed of labradorite, pyroxene and chlorite.

The plagioclase of the dolerites is labradorite or anorthite; it may be quite fresh, or much decomposed, altering in the latter case to an aggregate of minute granules of epidote, calcite, and occasionally of quartz. In thin section the augite is usually of a pale violet-brown tint. It mostly occurs in large ophitic masses, enclosing lath-shaped crystals and microlites of felspar. In altered rocks the augite is partially, sometimes

FIG. 93. Olivine-dolerite, Derbyshire.

Pl. Plagioclase. *A.* Augite. *O.* Olivine.

(*From a photograph by R. H. Rastall.*)

even completely, replaced by a scaly and fibrous aggregate of some chloritic mineral. The original hornblende of the hornblende-dolerites is usually the common brown variety. In the so-called *epidiorites*, however, it is of a pale green colour (uralite, actinolite, smaragdite), and is produced by paramorphism of the augite. The olivine of the olivine-bearing dolerites is

rarely quite fresh, being stained brown with limonite, blackened with magnetite-dust, or completely replaced by serpentine or calcite. When quartz occurs in the dolerites it usually forms a micrographic intergrowth with felspar, and the resulting micropegmatite is interstitial between the other constitutents (*e.g.* in dolerites of the Ratho type among the Carboniferous Rocks of Scotland). Such rocks are intimately related to the dioritic granophyres or markfieldites. (See p. 219).

Among accessory minerals the iron-ores, magnetite and ilmenite are always more or less abundantly present, the latter giving rise, when altered, to leucoxene (an amorphous variety of sphene). Pyrites is sometimes present in disseminated granules, and apatite in six-sided needles. Quartz, calcite, epidote, chlorite and serpentine are common secondary minerals; and these minerals are often distributed in veins and nests through the rocks.

The structure of the dolerites is characteristically ophitic; but in some cases a granular structure prevails. This is due to the occurrence of the augite in round granules, instead of in large ophitic plates enveloping the lath-shaped felspars. Where porphyritic structure is developed, phenocrysts of felspars, and sometimes of olivine and augite, are embedded in a groundmass of felspar microlites and granular augite. Interstitial glassy matter is only found as a marginal phenomenon. The Carboniferous intrusions of the Midland Valley of Scotland afford excellent examples of nearly all the varied types of structure that have been met with in the dolerites. (See p. 338).

ANALYSES OF DOLERITES.

	I. Quartz-dolerite Cauldron Snout.	II. Dolerite Canner.	III. Dolerite Rowley Rag.	IV. Dolerite Clee Hill.	V. Dolerite N.W. Highlands.
SiO_2 - -	51.22	49.53	49.0	48.4	47.45
Al_2O_3 - -	14.06	15.05	15.3	13.4	14.83
Fe_2O_3 - -	4.32	4.49	2.6	4.0	2.47
FeO - -	8.73	9.07	8.2	8.5	14.71
MgO - -	4.42	4.25	4.9	6.5	5.00
CaO - -	8.33	8.08	8.2	8.6	8.87
K_2O - -	1.25	1.25	2.6	2.1	.99
Na_2O - -	2.55	3.93	2.5	3.1	2.97
H_2O - -	1.47	2.53	3.3	2.2	1.00
TiO_2 - -	2.42	1.76	2.8	3.1	1.47
Other constits.	.90	.89	—	—	.36
	99.67	100.83	99.4	99.9	100.12

I. Quartz-dolerite, Whin Sill, Cauldron Snout (Teall.)
II. Porphyritic Olivine-Dolerite, Intrusive Sill, Ealaist Canner (W. Pollard).
III. Dolerite, Rowley Rag (J. H. Player).
IV. do. Clee Hill (J. H. Player).
V. do. N. side of Scourie Bay, N. W. Highlands (Teall).

The intrusive character of the dolerites is especially shown by their contact phenomena: baking or "porcellanization" of shales: formation of banded and spotted rocks (the so-called *desmoisites* and *spilosites*), and of hornstone-like rocks rich in alkalies (*adinoles*).[1]

The chemical composition of some typical British dolerites is shown in the table on p. 224.

FIG. 94. Teschenite, Lamlash, Arran.
Pl. Plagioclase. *A.* Augite. *O.* Olivine.
(*From a photograph by R. H. Rastall.*)

THE MUGEARITE-TESCHENITE FAMILY.

The rocks comprised in this family may be regarded as the hypabyssal equivalents of the alkali-gabbros—the mugearites being allied to the essexites, and the

[1] Lossen: Ueber den Spilosit und Desmoisit Zinckon's, *Zeits. Deutsch. Geol. Gesell.*, vol. xviv. (1872), pp. 701-786.

teschenites to the nepheline-gabbros. The **mugearite** type is described by Harker[1] as characterized by high alkalies and low magnesia and lime. Felspars rich in alkalies make up 70 per cent. of the rock. They appear under the microscope as lath-shaped crystals imparting a trachytic character to the rock. The felspars consist chiefly of oligoclase with subordinate orthoclase. The remaining constituents are olivine, augite, iron-ore, and apatite.

The **teschenites** or **analcime-dolerites** are dyke rocks essentially composed of plagioclase felspar, augite and analcime. Olivine is also a frequent constituent. With regard to the analcime, it is an open question whether this mineral is an original constituent, or produced by the decomposition of nepheline, as is considered to be the case in the typical teschenites of Silesia or Moravia.[2] In the figure on page 225 the analcime cannot be distinguished, as it occurs in small interstitial patches.

The following table gives some analyses of typical teschenites and mugearites:—

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[1] The Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 265.

[2] Lindgren: *Proc. Calif. Acad. Sci.*, vol. iii. (1890), p. 29.
Pirsson: *Journ. of Geol.*, vol. iv., 1896, p. 679.
Cross: *Journ. of Geol.* vol. v. (1897), p. 684.
Pelikan: *Tschermak's Min. u. Pet. Mitt.*, vol. xxv., 1900 p. 113.

ANALYSES OF TESCHENITES AND MUGEARITES.

	I. Mugearite, Skye.	II. Teschenite, Silesia.	III. Teschenite, N. Berwick.	IV. Teschenite, Bathgate.
SiO_2	49·24	48·18	47·03	45·71
Al_2O_3	15·84	11·80	15·36	15·23
Fe_2O_3	6·09	9·79	3·38	2·84
FeO	7·18	5·90	7·35	6.93
MgO	3·02	6.05	5·10	8·11
CaO	5·26	7·50	8·47	7·34
Na_2O	5·21	3·46	4.32	3·96
K_2O	2·10	1·57	3·00	1·31
H_2O	2·69	3·20	2·82	6·24
TiO_2	1·84	—	2.64	1·64
P_2O_5	1·47	0·49	·73	·47
Other constits.	·59	·71	·47	·73
	100·53	98·65	100·67	100·51

I. Mugearite, Druim na Criche, 5 miles S.S.W. of Portree, Skye (W. Pollard). The Tertiary Igneous Rocks of Skye. *Mem. Geol. Surv.*, 1904, p. 263.

II. Teschenite, Boguschowitz, Silesia. Rosenbusch: *Gesteinslehre*, p. 176.

III. Teschenite, Craigleith Island, N. Berwick (W. Pollard). *Summary of Progress, Geol. Surv.*, 1906, p. 75.

IV. Teschenite, Sill at Blackburn, Bathgate (W. Pollard). *Summary of Progress, Geol. Surv.*, 1906, p. 74.

THE APLITE-PEGMATITE FAMILY.

The aplites are the most acid differentiation products of the granite magma. They are found in association with minettes, to which they are *complementary* in Brögger's sense, in narrow dykes in the neighbourhood of, or penetrating granitic intrusions.

Besides their high silica content, they have a considerable proportion of alkalies and a subordinate quantity of ferro-magnesian constituents. In consequence they are characterized by a light colour —white to buff. In the hand-specimens they present a remarkably even and fine-grained, or saccharoidal texture; while under the microscope the constituents show a remarkable degree of idiomorphism. The dominant constituent is felspar—a potash, soda or lime-bearing variety, according to the special type. The proportion of quartz varies.

According to the nature of the felspathic constituent and the proportion of quartz, the aplites may be sub-divided as follows:

Eurite [1] or **Granite-aplite** = orthoclase + quartz.

Soda-aplite = soda-felspar (anorthoclase, albite, etc.) + quartz.

Lestiwarite [2] or **Syenite-aplite** = orthoclase with little or no quartz.

Malchite [3] or **Diorite-aplite** = lime-bearing plagioclase with little or no quartz.

Mica (muscovite) occurs in small quantities in most aplites. In the malchites the coloured mineral is usually hornblende. Common accessory constituents are garnet, zircon, tourmaline, and apatite.

Pegmatites. The members of this peculiar group are allied to the aplites in composition, but differ

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[1] Daubuisson (1819).

[2] Brögger. Die Grorudit-Tinguait Serie, *loc. cit.*, p. 312.

[3] Osann: *Mitth. d. Grossh. Bad. Geol. Landesanstalt*, 1892, ii. p. 380.

from them in possessing an extremely coarse-grained texture, and in the prevalence of graphic structure ;[1] also in the variety of accessory minerals they contain. They are now generally considered to be true igneous products, and to represent one of the last phases of consolidation of the plutonic magmas. The super-heated water that was set free during the first consolidation of the magma, doubtless played an important rôle in their formation ; and it is to the concentration in this water of the rarer elements and compounds from the magma, that the crystallization of many of the rarer accessory minerals in the drusy cavities of the pegmatites, is to be attributed. Consisting essentially of quartz, felspar (orthoclase or microcline) and mica (muscovite or biotite) the pegmatites are the home of a great number of accessory minerals, among which may be mentioned garnet, tourmaline, datolite, zircon, eudialyte, apatite, epidote, orthite, topaz, cassiterite, corundum, and fluorspar. The pegmatite veins associated with the syenites of Norway are remarkable for an abundance of minerals containing rare earths,[2] while in those associated with gabbro masses, apatite is often a dominant important constituent.

THE BOSTONITE FAMILY.

The bostonites are the acid differentiation products of a magma allied in composition to nepheline-

[1] The name has reference to this structure : Gr. *πῆγμα* (Haüy : *Traité de Min.*, 1822, p. 536.

[2] Brögger : *Zeitsch. für Kryst.*, vol. xvi., 1890, *passim.*

syenite, or to the essexites; the complementary basic rocks being the camptonites. They are fine-grained to compact light-coloured rocks, occurring in dykes or in small intrusions. The essential component is an alkali-felspar (microcline, anorthoclase, perthite), but a very small quantity of biotite and hornblende may be present. The micro-structure is *trachytic*—a structure characterized by the occurrence of the felspars in small rod-like microlites, forming a groundmass in which phenocrysts of felspar may or may not be present. A parallel arrangement of the microlites is common.

The more acid members of the bostonite family, which contain free quartz, are termed **quartz-bostonites**. The type described by Professor Brögger[1] as **lindöite** is closely related to the bostonites.

THE TINGUAITE-SÖLVSBERGITE FAMILY.

The **sölvsbergites** and **tinguaites** are allied to the bostonites. Occurring as dykes in association with, or as marginal modifications of, nepheline-syenite intrusions, they are undoubtedly differentiation products of the magma which formed the main intrusion. Consequently they are rich in soda, but poor in lime and magnesia. The essential constituents of the sölvsbergite type are potash-felspar (orthoclase or microcline), soda-felspar (anorthoclase or albite), ægirine or a soda-hornblende. The same mineral combination, with the addition of nepheline,

[1] Die Grorudit-Tinguait Serie, *loc. cit.*

Analyses of Leucocrates.

	I. Aplite Garabal.	II. Bostonite Cowal.	III. Bostonite Orkneys.	IV. Bostonite Assynt.	V. Sölvsbergite Sölvsberget.	VI. Tinguaite Hedrum.
SiO_2 - -	75.8	56.4	52.00	75.20	64.92	56.58
Al_2O_3 - -	13.7	19.0	18.06	12.65	16.30	19.89
Fe_2O_3 - -	0.5	3.5	2.18	1.53	3.62	3.18
FeO - -	0.3	4.8	5.14	.28	.84	0.56
MgO - -	tr.	1.5	2.84	.26	.22	0.13
CaO - -	0.5	2.6	4.59	.60	1.20	1.10
Na_2O - -	1.9	4.5	3.78	5.67	6.62	10.72
K_2O - -	6.5	5.0	4.68	4.14	4.98	5.43
H_2O - -	0.3	2.6	1.84	.12	.50	1.77
TiO_2 - -	—	—	.98	.12	—	—
CO_2 - -	—	—	3.59	.10	—	—
MnO - -	—	—	.25	—	.40	0.47
	99.5	99.9	99.93	100.67	99.60	99.83

I. Aplite (Eurite), Vein in granite S.W. Damhain, near Loch Garabal, Argyleshire (J. H. Player).
II. Bostonite ("trachytic dyke"), Dunans, Cowal, Argyleshire (Player).
III. do., Onston Ness, Orkneys.
IV. Quartz-bostonite, Cnoc an Droighinn, Inchnadamff, Assynt (Pollard).
V. Sölvsbergite from Sölvsberget, Gran, Christiania (L. Schmelck).
VI. Tinguaite, Hedrum, Christiania district (G. Paykull).

characterizes the tinguaites. The micro-structure is the trachytic, with microlites of felspar and ægirine. Occasionally a porphyritic structure is developed by the occurrence of phenocrysts of felspar, nepheline, and ægirine.

The chemical composition of some typical leucocratic rocks is shown in the table on page 231.

THE LAMPROPHYRE FAMILY.

The name **lamprophyre** was first used by Gümbel in describing the mica-traps of the Fichtelgebirge. It was adopted by Rosenbusch as a general and comprehensive name for the group. The name has reference to the lustrous character of the rocks, due, in the case of the chief members of the family (the minettes and kersantites), to the presence of mica. In the other members of the family (the camptonites and vogesites, in which hornblende takes the place of mica) the name rather loses its original significance.

Rosenbusch sub-divides the lamprophyres, according to the nature of the felspars, into the following types:

Minette[1]	=	orthoclase + biotite.
Kersantite	=	plagioclase + biotite.
Vogesite.	=	orthoclase + hornblende.
Spessartite / **Camptonite**	=	plagioclase + hornblende.

[1] The term *minette* was introduced by Voltz in 1828. *Kersantite* was first used by Delesse. The term "*kersanton*" (the name of a village near Brest) is used in a more general sense by

This classification is unsatisfactory on account of the unimportant rôle played by the felspars, and the frequent difficulty in determining their nature owing to the presence of secondary products in the groundmass.

FIG. 95. Mica-lamprophyre, Edenside.
B. Biotite (bleached internally).
The groundmass is an aggregate of biotite, felspar and magnetite.
(*From a photograph by R. H. Rastall.*)

Barrois, so as to include both kersantites and mica-porphyrites, the latter having phenocrysts of plagioclase. *Vogesite*, *spessartite* and *camptonite* are introductions of Rosenbusch, who regards the spessartites as allied to the minettes, kersantites and vogesites, while the camptonites he groups with the monchiquites and alnöites, as being derived from a nepheline-syenite, or theralite, magma. The petrographical distinction between spessartite and camptonite depends chiefly on the greater basicity of the latter; quartz, for instance, is absent in the latter, but often present in the former. The hornblende of the camptonites is also a deep red-brown basic variety, while that of the spessartites is of a paler greenish-brown colour.

The ferro-magnesian constituents furnish a better means of classification. Classified with reference to these minerals, the lamprophyres may be subdivided into mica-lamprophyres, hornblende-lamprophyres, and augite-lamprophyres.

Speaking generally, the family may be described as comprising dark-coloured fine-grained rocks of intermediate or basic composition, with a porphyritic habit determined chiefly by the presence of pheno-

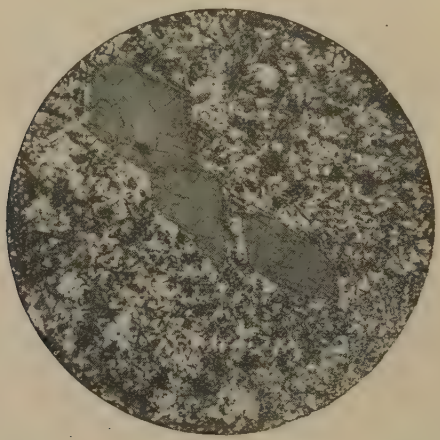

FIG. 96. Hornblende-lamprophyre (Camptonite), Campton Falls, New Hampshire.
Phenocrysts of hornblende in a groundmass of plagioclase and hornblende.
(*From a photograph by R. H. Rastall.*)

crysts of the ferro-magnesian constituent. These rocks occur as narrow dykes or small intrusions. Chemically they are characterized by a high percentage of alkalies (in particular of potash) in proportion to the silica content. A large pro-

portion of the potash goes to form mica, and in consequence of the abundant presence of this basic silicate, mica lamprophyres with even less than 50 per cent. of silica often contain free quartz. A marked characteristic of the family is the tendency to decomposition, with abundant development of carbonates.

The felspar occurs mainly as microlites in the groundmass: phenocrysts (orthoclase or plagioclase) are sporadic. The plagioclase is usually oligoclase. The felspars are rounded by corrosion, and the oligoclase phenocrysts are sometimes bordered by orthoclase. The mica occurs in lustrous scales and plates which, in the hand-specimen, are of a dark brown colour; while under the microscope, they are of a pale hue and show ragged edges. Sometimes the flakes appear to have undergone internal bleaching (see Fig. 95.) In convergent light the mineral is seen to be biaxial, but with a small optic axial angle. By alteration it passes into chlorite, thence into limonite, quartz and calcite (or dolomite). The hornblende, which may be brown or green, usually occurs in idiomorphic and rather elongated prisms. Augite appears in smaller crystals. It is usually of a pale colour when seen under the microscope. It is often quite decomposed, although the original crystal shape may be preserved. Accessory minerals are apatite in fine needles, iron-ores, and quartz. The quartz crystals are mostly rounded by corrosion, and in some cases there remain mere blebs, which are often bordered by a rim of fibrous hornblende. Olivine only occurs as pseudomorphs. Calcite and other carbonates (dolomite, magnesite) are rarely

absent. The presence of carbonates of lime, magnesia and iron is a striking feature in these rocks: in many cases they are so highly charged as to effervesce freely with acid. The carbonates occur either in scattered dust, or as pseudomorphs after original constituents, especially the olivine.

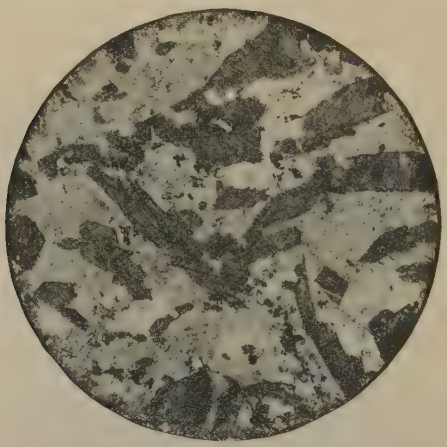

FIG. 97. Hornblende-lamprophyre (Spessartite), Inchnadamff, Loch Assynt, Sutherland.
The dark mineral is hornblende, the light mainly plagioclase.
(*From a photograph by R. H. Rastall.*)

THE MONCHIQUITE-ALNÖITE FAMILY.

The name **monchiquite**, which has reference to Serra de Monchique, in Portugal, was given by Rosenbusch to certain basaltic dykes in the nepheline-syenite district of Brazil. They are rocks without felspar, composed essentially of olivine together with augite, hornblende, or biotite. A glassy base is always present. They are thus allied in structure

Analyses of Melanocrates.

	I. Minette Odenwald.	II. Kersantite Thüringer Wald.	III. Camptonite Ardmuchnish.	IV. Camptonite Orkneys.	V. Monchiquite Orkneys.	VI. Alnöite Orkneys.
SiO_2 - -	51.15	52.12	42.22	39.13	42.51	35.54
Al_2O_3 - -	15.91	13.52	10.62	11.38	12.85	11.72
Fe_2O_3 - -	4.63	2.56	4.74	7.33	2.67	5.86
FeO - -	3.72	4.53	6.18	8.13	7.52	5.99
MgO - -	4.14	6.36	8.68	8.64	12.00	13.56
CaO - -	7.68	5.78	14.80	11.77	11.83	15.83
Na_2O - -	1.92	2.34	2.46	2.47	2.75	1.91
K_2O - -	5.97	5.36	1.41	1.93	2.15	2.24
H_2O - -	2.75	1.86	1.66	2.87	2.96	1.67
TiO_2 - -	—	1.20	2.49	4.02	—	2.03
CO_2 - -	2.12	3.59	3.57	2.41	3.46	4.30
Other constits.	—	.92	1.59	.42	0.83	0.32
	99.99	100.14	100.42	100.50	101.53	100.97

I. Minette, Leonhardskopf bei Flockenbach, Odenwald (quoted from Rosenbusch).
II. Kersantite, between Ober and Unter Neubrun, S.-E. Thüringer Wald (quoted from Rosenbusch).
III. Camptonite, dyke at Sailean Sligenach, West Coast of Ardmuchnish (W. Pollard).
IV. do., the West Dyke at Hoxa, Orkneys (Dr. Flett).
V. Monchiquite, Grainbank, Kirkwall, Orkneys (Dr. Flett).
VI. Alnöite, Navendale, Orkneys (Dr. Flett).

and composition to the augitite and limburgite flows. The olivine occurs in phenocrysts, the augite generally in small crystals in the groundmass. According as the mineral associated with the olivine and augite is biotite or hornblende, Rosenbusch sub-divides the rocks into hornblende- or biotite-monchiquite. The glassy base is often decomposed, and then gives rise to analcime. Possibly the analcime may also occur as an original constituent, as has been maintained by Pirsson and others.[1] The **alnöites** are a variety of biotite-monchiquite in which melilite and perovskite are largely developed in the groundmass.

The chemical composition of some typical melanocratic rocks is shown in the table on page 237.

THE PERKNITE[2] FAMILY.

These rocks are composed of various combinations of hornblende, augite, and rhombic pyroxenes, together with accessory biotite, olivine and iron-ores. They are heavy, dark-coloured rocks, and occur as deep-seated masses or as dykes. They are usually divided into pyroxenites and hornblendites, according as the dominant constituent is a pyroxene or a hornblende.

The following types have been established.

Pyroxenite[3]—with dominant monoclinic pyroxene.
Diallagite—with dominant diallage.
Websterite—or diallage-hypersthene rock.
Hypersthenite—with dominant rhombic pyroxene.

[1] Pirsson: *Journ. of Geol.* (1896), iv. pp. 679-690. Flett: *Trans. Roy. Soc., Edin.*, vol. xxxix. (1900), p. 889.

[2] περκνος dark. Turner: *Journ. of Geol.*, vol. ix., 1901, p. 507.

[3] Sterry Hunt (1862).

Hornblendite[1]—with dominant hornblende.

Hornblende-pyroxene-rock.

Eclogite—a variety of hornblende-pyroxene rock in which the hornblende is emerald-green (smaragdite), the augite, grass-green (omphacite). A third constituent is red garnet.

When typically developed, the members of the perknite family contain neither felspar nor olivine: by the addition of the former they pass into the norites and gabbros, and by the addition of the latter into the peridotites.

The chemical composition of some types is given in the following table.

ANALYSES OF PERKNITES.

	I. Websterite.	II. Hornblende-Pyroxene rock.	III. Pyroxenite.	IV. Hornblendite.
SiO_2	53·25	48·04	45·05	37·90
Al_2O_3	2·80	7·82	6·50	13·17
Fe_2O_3	·69	2·01	3·83	8·83
FeO	5·93	9·32	7·69	8·37
MgO	19·91	13·33	12·07	9·50
CaO	16·22	13·01	18·66	10·75
Na_2O	·19	·69	·94	2·35
K_2O	—	·48	·78	2·12
H_2O	·29	3.07	2·40	1·40
TiO_2	—	1·16	2·65	5.30
Other constits.	·70	2·03	·31	
	99·98	100·96	100 88	99·69

I. Websterite, Mt. Diablo.—W. A. Melville: *Bull. U.S. Geol. Surv.*, No. 168, p. 213.

[1] J. D. Dana (1880).

II. Hornblende-pyroxene rock, Mariposa County, California —W. F. Hillebrand : *Journ. of Geol.*, vol. ix., 1901, p. 509.

III. Pyroxenite, Brandberget, Gran, Norway—Von Schmelck : *Quart. Journ. Geol. Soc.*, vol. l., 1894, p. 31.

IV. Hornblendite, Brandberget, Gran, Norway — Von Schmelck : Quoted from Washington's Analyses, p. 345.

THE PICRITE FAMILY.

Picrites [1] were first described by Tschermak, as olivine-augite rocks intrusive in the Cretaceous and

FIG. 98. Enstatite-picrite, Lochinver, Sutherland.
E. Enstatite. *O.* Olivine. *f.* Felspar.
(*From a photograph by R. H. Rastall.*)

Eocene formations of the highlands between Neutitschein, Teschen and Bielitz in Moravia and Silesia. Similar rocks have since been noticed by Gümbel

[1] Name given by Tschermak (in 1866) on account of the high percentage of magnesia (bitter-earth) in these rocks (Gr. πικρός).

in the Fichtelgebirge (*Palæopikrit*), and other observers have recorded their occurrence in the Lower Devonian slates of the Rhine valley (Nassau, Ruhrthal, Wetzlar, etc.).

The picrites are dark, heavy rocks, composed mainly of olivine and augite, with a variable but always small amount of felspar. In addition to these minerals, brown biotite is sometimes present; while bright-green chloritic and serpentinous products, probably also a secondary hornblende (pilite), are usually developed at the expense of the ferro-magnesian minerals.

Hornblende-picrite [1] is a similar rock, in which brown hornblende is present instead of the usual augite. A colourless augite (malacolite) is, however, sometimes associated with the hornblende.

A characteristic feature of the picrites is the *lustre-mottling*, seen in hand-specimens. This phenomenon is produced by the interrupted reflection of light from the cleavage-surfaces of the augite or hornblende, as the case may be, the interruption being due to a pœcilitic inclusion of grains of olivine.

Chemically these rocks contain little silica, a small proportion of alumina (10 per cent. or less), and a very large amount of magnesia, ranging from 15 to 30 per cent.; while the total alkalies are usually below 2 per cent. The specific gravity lies between 2·8 and 3. In the following table are some analyses of types.

[1] Bonney (*Quart. Journ. Geol. Soc.*, 1881, p. 454).

ANALYSES OF PICRITES.

	I. Picrite, Little Assynt.	II. Picrite, Blackburn.	III. Picrite, Anglesey.	IV. Picrite, Gümbelberg.
SiO_2	46·23	44·73	42·94	40·79
Al_2O_3	6·30	11·89	10·87	10·41
Fe_2O_3	4·30	4·85	3·47	3·52
FeO	7·07	6·61	10 14	6·39
MgO	25·13	10·77	16·32	23·34
CaO	6·08	7·69	9·07	8·48
Na_2O	1·08	2·77	·90	1·71
K_2O	·33	·89	·15	0·71
H_2O	3·78	7·64	6·09	4·04
TiO_2	—	1·53	—	—
Other constits.	·33	1·06	—	—
	100·63	100·43	99·95	99·39

I. Picrite, Little Assynt, Scotland (Grant Wilson).
II. „ Sill at Blackburn, Bathgate Hills (W. Pollard).
III. Picrite, Anglesey (J. H. Phillips).
IV. Picrite, Gümbelberg (Tschermak).

THE PERIDOTITE FAMILY.

The peridotites are ultrabasic rocks without felspar and composed mainly of olivine, the remaining constituents being one or more members of the pyroxene-hornblende group together with iron-ore, spinel or garnet. The rocks occur chiefly as dykes. They are especially remarkable for their excessively basic character and high specific gravity: $SiO_2 = 35–45\%$; $Al_2O_3 = 0–6\%$; $FeO = 8–10\%$; $CaO = 0–2\%$; $MgO = 35–48\%$. Alkalies are present in small quan-

tities only. Sp. G. 3·0–3·3. By decomposition they give rise to serpentinous rocks.

The following names have been applied to some of the combinations:—

Dunite [1]—mainly composed of olivine, together with chromite and other spinels, and sometimes garnet (pyrope).

Wehrlite [2] = olivine + augite (diallage).

Saxonite or **Harzburgite** [3] = olivine + rhombic pyroxene.

Lherzolite [4] = olivine + augite (diallage) + hypersthene.

Cortlandtite [5] = olivine + hornblende + hypersthene.

Scyelite [6] = olivine + biotite + hornblende.

Eulysite [7] = olivine + augite (diallage) + garnet; a type analogous to eclogite.

Since the number of mineral combinations is very large whilst the occurrences are limited, the divisions in the above table are unnecessarily numerous for such a small family. A simpler classification is by the ferromagnesian constituents, as follows:

Dunite—olivine rock.

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[1] So named from the Dun Mountains in New Zealand, where rocks of this type were discovered by Hochstetter in 1859.

[2] Von Kobell (1838).

[3] The former name was proposed by Wadsworth in 1884, on account of the occurrence of these rocks in Saxony; the latter by Rosenbusch in 1885, in reference to the well-known Harzburg occurrence.

[4] Named by Delamétherie after Lake Lherz in the Pyrenees.

[5] Name suggested by G. H. Williams for a type occurring in the "Cortlandt Series" of Peekskill on the Hudson River, N.Y.

[6] J. W. Judd: *Quart. Journ. Geol. Soc.*, vol. xli. (1885).

[7] Name given by A. Erdmann (1849).

Hornblende-peridotite = olivine + hornblende.

Pyroxene-peridotite—including wehrlite, saxonite and lherzolite.

Hornblende-pyroxene-peridotite—including cortlandtite and eulysite.

Hornblende-biotite-peridotite—including scyelite.

ANALYSES OF PERIDOTITES.

	I. Dunite, New Zealand.	II. Wehrlite, Loch Garabal.
SiO_2	42·8	38.6
Al_2O_3	—	3·7
Fe_2O_3	—	7·6
FeO	9·4	7·8
MgO	47·4	27.7
CaO	—	7·7
Na_2O	—	—
K_2O	—	·2
Loss on ignition	·6	6·4
	100·2	99·7

I. Dunite, Dun Mountains, New Zealand (Reuter).
II. Wehrlite, Loch Garabal (J. H. Player).

TABLE SHOWING THE MUTUAL RELATION OF THE FELSPAR-FREE ROCKS.

Olivine-free rocks (*Perknites*).	*Olivine-bearing rocks* (*Peridotites*).	*Rocks with a little felspar* (*Picrites*).
Hornblendite	Hornblende-peridotite	Hornblende-picrite
Diallagite	Wehrlite	Picrite proper or pyroxene picrite
Hypersthenite	Saxonite	
Websterite	Lherzolite	
Hornblende-pyroxene-rock	Cortlandtite, etc.	Hornblende-pyroxene-picrite
Eclogite	Eulysite	

SERPENTINES.

By alteration, under the influence of surface agencies, the peridotites give rise to serpentinous rocks; and there is no doubt that a great number of serpentines have originated in this way. On the other hand, some have been shown to be derived from augitic rocks, such as gabbro, diabase, etc. (*antigorite-serpentine*); and others, from hornblendic rocks, as in the case of the Rauenthal serpentine, described by Weigand. Fragments of unaltered olivine, diallage, and bastite (the latter derived from a rhombic pyroxene) are often found embedded in serpentine, thus furnishing a proof of the mode of the origin of these rocks. Again, their mode of occurrence, in dykes and bosses, leads to the same conclusion.[1] The chemical changes necessitated by the conversion of olivine and augite to serpentine are illustrated by the analyses given on page 247. The chemical changes illustrated by these analyses can be expressed by the following equations:

(1) *Alteration of olivine to serpentine.*

$$2[2MgO.SiO_2] + CO_2 + 2H_2O = MgCO_3 + 3MgO.2SiO_2.2H_2O$$

(2) *Alteration of enstatite to serpentine.*

$$4[MgO.SiO_2] + CO_2 + 2H_2O = MgCO_3 + 2SiO_2 + 3MgO.2SiO_2 2H_2O$$

[1] See a paper by Prof. Bonney and Miss Raisin on "The microscopic structure of minerals forming serpentine, and their relation to its history." *Quart. Journ. Geol. Soc.*, vol. lxi. (1905), p. 690.

Serpentines are dull-green and red, often mottled rocks. They are so soft that they can be easily scratched, or even cut with the pen-knife. Veins of fibrous chrysotile and steatite frequently traverse them. In some cases the serpentinous mineral is disseminated through limestone, as in the rocks known as *ophicalcite*.

ANALYSES SHOWING THE COMPOSITION OF SERPENTINE, AND ITS MODE OF ORIGIN FROM OLIVINE AND PYROXENE.

	Olivine. Snarum. (Helland.)	Serpentine derived from it. (Helland.)	Pyroxene, Montville, New Jersey.	Serpentine derived from it.	Theoretical Composition of Serpentine. $3MgO.2SiO_2.2H_2O$
SiO_2 - -	41 32	42.72	54.22	42.38	43.48
Al_2O_3 - -	0.28	0.06	0.59	0.07	—
Fe_2O_3 - -	—	—	0.20	0.97	—
FeO - -	2.39	2.25	0.27	0.17	—
MgO - -	54.69	42.52	19.82	42.14	43.48
CaO - -	—	—	24.71	—	—
H_2O - -	0.20	13.39	0.14	14.12	13.04
CrO - -	0.05	tr.	—	—	—
	98.93	100.94	99.95	99.85	100.00

CHAPTER III

THE VOLCANIC ROCKS.

THE volcanic rocks can be classified in the same manner as the plutonic rocks. The same limits of 66 and 52 per cent. of silica separate the acid from the intermediate and the intermediate from the basic groups respectively, the small ultra-basic sub-group being represented by the rocks known as limburgites and augitites. The calc-alkali series is represented by the dacites, andesites and basalts; the alkali series by the rhyolites, trachytes and alkali-basalts; while the middle or monzonite series is represented by the trachy-andesite series.

This classification is shown in the following scheme, where for comparison the corresponding plutonic types are inserted in square brackets.

CLASSIFICATION OF THE VOLCANIC ROCKS.

	Alkali Series.	*Trachy-andesite Series.*	*Calc-alkali Series.*
Acid Group	RHYOLITE [*Granite*]	TOSCANITE [*Adamellite*]	DACITE [*Granodiorite*]
Inter-Group	TRACHYTE [*Syenite*]	TRACHY-ANDESITE [*Monzonite*]	ANDESITE [*Diorite*]
Basic Group	ALKALI-BASALT [*Alkali-gabbro*]	CIMINITE[1] [*Kentallenite*]	BASALT [*Gabbro*]

[1] The Ciminites range in silica-content from 54 to 57 per cent.

The ratio of alkali-felspar and calc-alkali-felspar is a variable quantity in these rocks; when the alkali-felspar is balanced by the calc-alkali-felspar the rocks belong to the trachy-andesite series, but a preponderance of the alkali-felspar would bring them into the alkali series. As pointed out when dealing with the plutonic rocks, every gradation between the types established by the scheme of classification exists not only vertically, by variation in silica content, but also laterally by variation in the ratio of the alkali and calc-alkali molecules. As with the plutonic rocks also the alkali-series may be further divided into sub-series, in which felspathoids, soda-felspars, and potash-felspars respectively predominate. Thus the *phonolites* are nepheline-bearing trachytes and both soda-trachytes and potash-trachytes exist. Again, the *tephrites* and *basanites*, the *leucite-* and *melilite-basalts* are felspathoid-bearing alkali-basalts.

THE RHYOLITE FAMILY.

The **rhyolites**[1] are the volcanic equivalents of the granites, or, in other words, rocks produced by the consolidation of a granite magma under volcanic conditions. They are highly acid, containing, in most cases, free silica in the form of quartz.

[1] The name *rhyolite* was given to these rocks by Richthofen (1860) on account of the fluidal structure frequently shown by them (Gr. ῥύαξ). They have also been termed *quartz-trachytes*; and again *liparites* (Roth. 1860), this designation having been given them on account of their occurrence in the Lipari Islands. A crystalline and granitoid variety of rhyolite has been described under the name of *nevadite* by Richthofen.

Having been poured out as subaerial or submarine lavas, they usually present marked fluidal, spherulitic and perlitic structures. Occasionally they are compact, but more frequently they have a porphyritic structure. The phenocrysts are quartz and felspar, imbedded in a light-coloured trachytic groundmass, which is mainly composed of microlites of felspar. Prisms of augite and hornblende, plates of biotite and granules of magnetite also occur. A glassy base is present in variable proportion, according to the conditions that prevailed during cooling. If the proportion of glass is so large that the crystals are subordinate, the rocks are known as **obsidians**. Accessory minerals are magnetite, tridymite, apatite, cordierite, garnet, sphene and allanite.

The quartz is sometimes bi-pyramidal, but oftener without definite shape. Though usually pellucid and colourless, it has frequently a dark-coloured or smoky hue. In some rhyolites the conditions of eruption have been such as to prevent the separation of quartz; but the high percentage of silica shown by chemical analysis facilitates the correct diagnosis of such rocks.

The felspar is usually sanidine—a glassy variety of orthoclase. It occurs frequently in large tabular crystals, which are glassy, clear and much fissured; but also in smaller and less regular grains. In addition to the orthoclase, there is often present a triclinic felspar. This is sometimes oligoclase, but more frequently albite, soda-microcline or anorthoclase. In some rhyolites the sole porphyritic constituent is a soda-felspar, having the same glassy

habit as the potash-felspar (sanidine). According to the predominance of potash-felspar or soda-felspar, the rhyolites may be divided into **potash-rhyolites** and **soda-rhyolites**. The latter comprise the more acid pantellerites. (See page 256.)

Fluxion-structure is often shown in the groundmass by the beautiful wavy lines of flow which sweep round the larger embedded grains. The same structure is also occasionally brought out under the microscope by the strict parallelism of the felspar-microlites, or by bands of crystallites and trichites in the glassy rhyolites and obsidians.

The identity of many so-called *felsites* with the rhyolites has been demonstrated by the researches of Rutley and Allport.[1] Many of these rocks, consisting of a cryptocrystalline aggregate of quartz and felspar (felsitic matter), in which porphyritic crystals of quartz and felspar are often embedded, were found to possess traces of perlitic, spherulitic and fluidal structures. (See Fig. 21.) These structures, being characteristic of rocks that have consolidated in a vitreous or semi-vitreous condition, indicated the true nature of the rocks that possess them. They are, in fact, ancient flows of rhyolitic lava that have subsequently acquired a cryptocrystalline structure by a gradual process of devitrification. Like the rhyolites, they contain porphyritic crystals of both

[1] Rutley: *Quart. Journ. Geol. Soc.*, vol. xxxvii. (1881), p. 403, and vol. xliv. (1888), p. 74; Allport: *ibid.*, vol. xxxiii. (1877), p. 449. It was, however, Clifton Ward who first showed that the Welsh felsites were acid volcanic rocks: *Quart. Journ. Geol. Soc.*, vol. xxxi. (1875), p. 388.

unstriped and striped felspar, and their chemical composition shows that they may be separated into a potash type and a soda type. These lavas are found interbedded with sedimentary strata, in association with tuffs and breccias, which were doubtless a product of the same volcanic activity.

A nodular character is very common in rhyolitic lavas. The nodules vary in size from a small marble to a man's fist; in some cases they are even larger. Probably in many instances the nodules are enlarged spherulites; but they have also been ascribed to contraction on cooling as in true perlitic structure, and to the infilling of original vesicles with quartz and agate by infiltration (*lithophysæ* of Richthofen.

The chemical composition of the chief types is given in the following table:

ANALYSES OF RHYOLITES.

	I. Soda-Rhyolite, Brittas.	II. Potash-Rhyolite, Tardree.	III. Potash-Rhyolite, Wrekin.	IV. Potash-Soda Rhyolite, Fishguard.	V. Acid Pantellerite, Mt. St. Elmo.
SiO_2	77·29	76·4	75·4	68·01	67·48
Al_2O_3	14·62	14·2	13.2	17·48	9·70
Fe_2O_3		1·6	·8	0·41	7·42
FeO	—	—	·6	—	2·21
MgO	·38	—	·2	0·46	0·77
CaO	tr.	·6	·4	tr.	1·45
Na_2O	7·60	1·8	1·1	5·77	7·21
K_2O	·16	4·2	7·0	7·08	2·94
H_2O	·57	1·5	·7	0·73	0·96
	100·62	100·3	99·4	99·94	100·14

I. Soda-Rhyolite.—Brittas Bridge, Co. Wicklow, Ireland (F. H. Hatch).

II. Potash-Rhyolite.—Tardree, Co. Antrim, Ireland (J. H. Player).

III. Potash-Rhyolite.—Lea Rock, near the Wrekin (J. H. Player).

IV. Potash-Soda-Rhyolite.—Goodwick, Fishguard (Tadman).

V. Acid Pantellerite.—Monte St. Elmo, Pantellaria (Förstner).

THE TRACHYTE FAMILY.

This great family embraces all the members of the alkali series of volcanic rocks of intermediate composition, and thus corresponds to the syenite family among the plutonic rocks.

The name *trachyte* was originally applied to all volcanic lavas which, owing to their vesicular texture,[1] are rough to the touch. The use of the term, however, has been gradually limited. First, it was restricted to rocks of intermediate composition; and then these were further subdivided according to the nature of the dominant felspar. This mineral, which occurs in glassy porphyritic crystals, is either the potash variety (orthoclase), a soda felspar (anorthoclase), or a soda-lime plagioclase (oligoclase, andesine). The term trachyte is now applied solely to rocks containing dominant alkali-felspars; while rocks with dominant lime-bearing plagioclase are now termed andesites, on account of their abundant occurrence in the Andes of S. America.

The trachytes are divisible into three sub-families:

[1] Gr. τραχύς, rough (Haüy: *Traite de Min.*, 1822, p. 579).

1. The Phonolites—with dominant nepheline or other felspathoid.
2. The Soda-Trachytes or Pantellerites—with dominant soda-felspar (anorthoclase).
3. The Potash-Trachytes or Trachytes proper—with dominant potash-felspar (sanidine or glassy orthoclase).

FIG. 99.

Phonolite.

n. Nosean. *s*. Sanidine. *h*. Hornblende.

The microlites are Sanidine, and the square and hexagonal sections, Nepheline. (*After Fouqué and Lévy.*)

The **phonolites**[1] are the volcanic equivalents of the nepheline-syenites. They are rocks composed essentially of sanidine, nepheline and a ferro-magnesian constituent. (See Fig. 99.) Sometimes

[1] Name (from Gr. φωνή) introduced by Klaproth.

the place of the nepheline is taken by leucite, and then the rock is termed **leucite-phonolite**. **Leucitophyre** is the name given by Rosenbusch to a type containing both nepheline and leucite together with sanidine.[1] Associated with the nepheline or leucite are sodalite, nosean and haüyne. The ferro-magnesian constituent is generally a green augite, which is sometimes a soda variety with low extinction angles (ægir-

FIG. 100.

Trachyte, Peppercraig, Garlton Hills, near Haddington. (Between crossed nicols.)

Or. Orthoclase (Sanidine) with glomero-porphyritic structure.

A. Augite.

The microlites are felspar.

ine). Brown mica and hornblende occur as accessory constituents. Other accessories are apatite, iron-ore (magnetite), sphene and melanite (black garnet).

[1] The term was used originally by Coquand for leucite rocks generally.

Natrolite and other zeolitic minerals result from the alteration of the nepheline.

The phonolites are usually very compact rocks of a greyish-green colour, with a spotted appearance. They ring under the hammer, and hence have been termed *clinkstone*. A platy and spheroidal mode of weathering is a characteristic feature, the decomposing rock having a concentric shelly structure like that of an onion.

The **soda-trachytes** or **pantellerites**, first described by Förstner[1] and so-named by him because of their occurrence on the island of Pantelleria, off the coast of Sicily, are a peculiar group of rocks in which the dominant felspar is a member of the triclinic soda-potash series (anorthoclase). Chemically these rocks are characterised by a high alkali-content, with dominant soda.[2] Beside anorthoclase, ægirine-augite, diopside, cossyrite, and more rarely hornblende, may be present. The groundmass may be glassy or trachytic with abundant felspar microlites.

The **potash-trachytes**, or **trachytes** proper, are light-coloured, rather porous rocks consisting mainly of felspar, ferro-magnesian minerals forming only a small proportion of the whole. The phenocrysts of orthoclase have a glassy habit (sanidine). They occur either as tabular crystals twinned on the Carlsbad law, or as irregular grains. In the ground-

[1] *Zeitsch. für Kryst.*, vol. v. (1881), p. 348, and vol. viii. (1884), p. 125.

[2] The high silica-content of many of the original pantellerites described by Förstner, points to a rhyolite rather than to a trachyte type. See analysis on p. 250.

mass, however, the felspar appears in long needles and microlites, which are unstriated, and doubtless consist largely of orthoclase. A parallel arrangement, due to flow, is often exhibited and this constitutes the typical *trachytic* structure. Interstitial matter, when present, is usually felsitic, a true glassy base being rare. The ferro-magnesian minerals are brown mica, green or blue amphibole

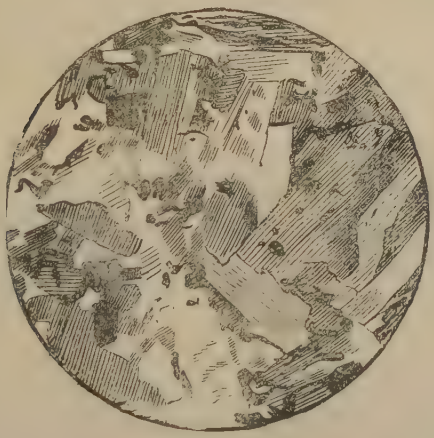

FIG. 101.

Trachyte, Bass Rock.
(Between crossed nicols.)
Composed almost entirely of lath-shaped crystals of orthoclase (sanidine).

and colourless or pale-green pyroxene (malacolite). According to the nature of the dominant species, the trachytes may be divided into **mica-trachytes** **amphibole-trachytes**, and **pyroxene-trachytes**.

Accessory minerals are abundant: namely, iron-

ores, zircon, apatite, sphene, haüyne and nosean. Quartz is occasionally present in small quantity, indicating thus a passage to the rhyolites. On the other hand, some trachytes have had their silica percentage increased, subsequently to consolidation, by hydro-thermal impregnation with secondary silica (chalcedony, hyalite, opal, etc., or quartz).

Trachytes occur in flows, dome-shaped masses, and dykes, in numerous volcanic districts: Auvergne, Siebengebirge, Henry Mountains in America, etc.

The chemical composition of some British types is shown in the table on page 259.

THE TRACHY-ANDESITE FAMILY.

The **trachy-andesites** are effusive rocks corresponding to the monzonites of the plutonic class. They are rocks of intermediate composition, in which orthoclase and lime-bearing plagioclase are equally developed. They thus occupy a middle position between the trachytes and the andesites, as the monzonites do between the syenites and the diorites. Rocks of this type are of limited occurrence, but, according to Washington, they occur among the volcanic districts of Italy, in the Euganean Hills, and among the Siebengebirge lavas.[1]

The **toscanite** family embraces the more acid

[1] H. S. Washington: *Journ. of Geol.*, vol. iv. (1896), pp. 547 and 881. Washington distinguishes a type with alkali-felspar and acid plagioclase (andesine to oligoclase), which he terms *domite*, from a type with alkali-felspar and basic plagioclase (labradorite to anorthite), which he styles *vulsinite*.

Analyses of Trachytes and Phonolites.

	I. Soda-trachyte Hamilton Hill.	II. Trachyte Braid Hills.	III. Trachyte Peppercraig.	IV. Trachyte Kae Heughs.	V. Phonolite Traprain Law.	VI. Phonolite Wolf Rock.
SiO_2	64.38	63.02	62.61	61.35	56.8	56.46
Al_2O_3	16.98	15.50	18.17	16.88	19.7	22.29
Fe_2O_3	4.04	4.81	0.32	.41	2.2	2.70
FeO	—	.13	4.25	5.01	3.5	.97
CaO	1.08	2.67	2.58	2.39	2.2	1.47
MgO	.28	.62	0.74	.44	.4	tr.
Na_2O	7.57	4.46	6.49	5.26	4.3	11.13
K_2O	4.30	3.96	4.02	6.12	7.1	2.81
H_2O	1.64	2.49	.80	1.70	2.5	2.05
TiO_2	—	.43	—	—	.5	—
Other constits.	—	2.11	.20	.26	.2	—
	100.27	100.20	100.18	99.82	99.4	99.88

I. Soda-trachyte, Hamilton Hill, N.E. of Peebles (J. J. H. Teall).
II. Trachyte, Morton Hall, Braid Hills, near Edinburgh (W. Pollard).
III. Trachyte, Peppercraig, Haddingtonshire (J. Grant Wilson).
IV. Trachyte, Kae Heughs, Garlton Hills, Haddingtonshire (J. Grant Wilson).
V. Phonolite, Traprain Law, Haddingtonshire (J. H. Player).
VI. Phonolite, Wolf Rock, Cornwall (J. A. Phillips).

members of the trachy-andesite series—*i.e.*, those with a silica-content of from 66 to 73 per cent. It corresponds to the adamellite family among the plutonic rocks. The toscanites contain phenocrysts of both potash-felspar and plagioclase (andesine to labradorite), together with quartz and a ferro-magnesian mineral (biotite, augite, or hypersthene), embedded in a glassy groundmass. According to Washington, rocks of this type are found at Bracciano, Cerveteri, Tolfa, Monte Amiata, in Central Italy; and they are probably represented in the oceanic islands of the Atlantic basin (at the Azores, Madeira, Teneriffe, and Ascension).[1]

The small sub-family of **Ciminites** is the most basic division of the trachy-andesite series. It corresponds to the basic monzonite, or kentallenite, division of the plutonic rocks. The name is derived by H. S. Washington[2] from Monte Cimini, in the Viterbo district of Italy, where the type rock occurs. It consists of phenocrysts of augite, olivine and felspar in a groundmass of felspar microlites, augite granules, magnetite and apatite. The felspars consist of alkali-felspar (orthoclase) and a basic plagioclase. The silica percentage varies from 54 to 57 per cent. Allied types are the shoshonite and absarokite of Iddings.[3]

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[1] H. S. Washington: *Journ of Geol.*, vol. v. (1897), p. 349.
[2] *Journ. of Geol.*, vol. v. (1897), p. 349.
[3] *Journ. of Geol.*, vol. iii. (1895), p. 935.

ANALYSES OF TRACHY-ANDESITES.

	I. Toscanite, Monte Cucco.	II. Trachy-Andesite, Bolsena.	III. Ciminite, Monte Cimini.
SiO_2	66·24	58·21	55·46
Al_2O_3	15·64	19·90	15·36
Fe_2O_3	1·16	4·07	1·34
FeO	2·19	0·87	4·50
MgO	0·89	0·98	7·90
CaO	2·17	3·58	6·69
Na_2O	2·05	2·57	1·79
K_2O	6·60	9·17	6·63
H_2O	3·25	0·74	0·38
	100·19	100·09	100·05

I. Toscanite, Monte Cucco, Cerveteri, Italy (H. S. Washington).

II. Trachy-andesite (Vulsinite), Bolsena, near Orvieto, Italy (H. S. Washington).

III. Ciminite, Fontana di Fiesoli, Monte Cimini, near Viterbo, Italy (H. S. Washington).

THE ANDESITE FAMILY.

This large family includes volcanic rocks of intermediate composition belonging to the calc-alkali series. It corresponds to the diorite family of the plutonic rocks.

The **andesites** are dark-coloured, compact or vesicular, semi-vitreous volcanic rocks occurring mainly as lava-flows, and more rarely as dykes. They are composed essentially of a glassy plagioclase felspar and a ferro-magnesian constituent, together with a glassy base. According to the nature

of the ferro-magnesian constituent, they may be divided into **hornblende-andesites**, **biotite-andesites** and **pyroxene-andesites**; and intermediate varieties are produced by the various combinations of these minerals. (See Figs. 102 and 103.)

The hornblende is the common brown variety, occurring in well-formed lozenge-shaped crystals,

FIG. 102.

Andesite (Mica-andesite).

Porphyritic crystals of Plagioclase Felspar (*y*) and Mica (*m*) imbedded in microlitic ground-mass. (*After Fouqué and Lévy.*)

which often have a dark border, due to the corrosive action of the molten magma in which they floated when first formed. The monoclinic augite is of a pale brown colour and is non-pleochroic. The hypersthene is pleochroic, in pale green and reddish tints.

Both occur in well-formed crystals, giving square sections with truncated corners. The felspar occurs in good-sized crystals, producing a marked porphyritic structure. In its glassy character it resembles sanidine, but it is distinguished therefrom by its twin-striation. Accessory minerals are magnetite, apatite, garnet, sphene, olivine, allanite, and cor-

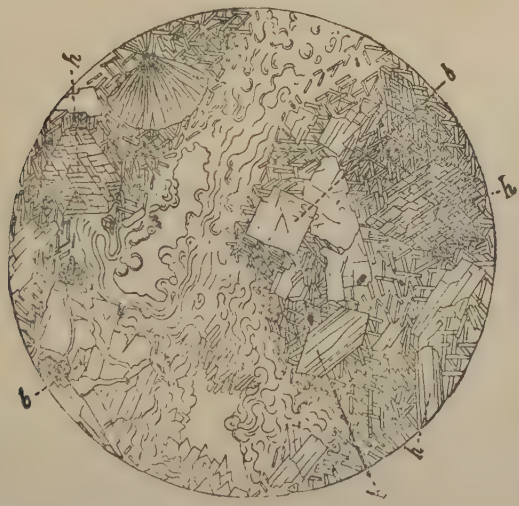

FIG. 103.

Hornblende-Andesite.

Porphyritic crystals of Plagioclase Fel-par (*b*) and Hornblende (*h*), in a microlitic ground-mass. (*After Fouqué and Lévy.*)

dierite. Quartz is sometimes present. With an increasing proportion of this mineral the andesites pass into dacites. Some rocks, however, that from chemical analysis might be considered as dacites,

owe their acidity to secondary impregnation, by hydro-thermal agencies (warm springs containing dissolved silica), with chalcedonic and opaline silica. The groundmass of the andesites is usually microlitic, being composed of needles of felspar and an abundant glassy base. The latter is generally of a pale brown colour and either clear or partially devitrified. By an increase in the proportion of this base, the rocks gradually pass into true andesitic glasses.

The andesites become much altered by atmospheric decomposition: the felspar, originally fresh and glassy, becomes turbid; the augite, partially or completely converted to chlorite; the hypersthene, to fibrous bastite; and the magnetite, to red oxide of iron. The vitreous base gives place to a dull stony mass; and the rocks become tinged red by much disseminated oxide of iron, or green by diffused chlorite; these minerals, together with zeolites and carbonates, also filling the vesicular cavities. Altered andesites have been termed porphyrites and propylites by some authors. Modern English writers, however, use the word porphyrite in a different sense. (See page 219.)

The family of the **dacites**[1] comprises the most acid members of the calc-alkali series of volcanic rocks, and as such corresponds to the granodiorites in the plutonic class. With diminishing silica percentage they pass into andesites, from which they are mineralogically distinguished by the presence of

[1] Name introduced by Stache for the quartz-andesites of Transylvania.

quartz. Phenocrysts of this mineral occur in corroded pyramids, with inlets of the glassy groundmass. The remaining constituents (plagioclase and one or more of the ferro-magnesian minerals—hornblende, augite, hypersthene or biotite), possess the same general characteristics as those of the andesite family. (See page 262.)

ANALYSES OF ANDESITES.

	I. Dacite, Lassen's Peak, California.	II. Hornblende-andesite, Mount Shasta.	III. Andesite, Blackford Hills, Scotland.
SiO_2	68·72	61·58	57·53
Al_2O_3	15·15	16·96	16·47
Fe_2O_3	1·16	1·75	4·42
FeO	1·76	2·85	3·23
MgO	1·28	3·67	1·32
CaO	3·30	6·28	6·16
Na_2O	4·26	3·94	4·13
K_2O	2·78	1·28	2·09
H_2O	·74	1·30	1·02
TiO_2	·31	·49	·91
Other constits. (chiefly CO_2)	·30	·25	3·27
	99·76	100·35	100·55

I. Dacite, East End of Chaos, Lassen's Peak, California (W. F. Hillebrand).

II. Hornblende-andesite, Mount Shasta, California (H. N. Stokes).

III. Andesite, Blackford Hills, near Edinburgh (E. G. Radley)

THE BASALT[1] FAMILY.

The **basalts** are dark-coloured lavas of basic composition and high specific gravity, representing the extrusive or volcanic type of the plutonic gabbros. When fresh, they are characterized by their black

FIG. 104. Crystal of Fused Hornblende in basalt.

colour, and minutely crystalline to compact texture and high density. When altered or decomposed by the action of the weather, they assume a reddish or greenish hue, and are much veined by decomposition products. A further stage of decomposition converts the basalt into a loose crumbling material known as

[1] The word "basalt" is one of the oldest in petrography. It is said to be derived from the Ethiopian word signifying an iron-bearing stone. According to Pliny, "invenit eamdem Ægyptus in Æthiopiâ, quem vocant basaltem, ferrei coloris et duritiæ, undè et nomen ei dedit."

wacke, which is but little removed from clay in composition. Microscopic examination of a fresh basalt shows it to be composed essentially of plagioclase

FIG. 105. Olivine-Basalt.

Porphyritic crystals of Olivine (*o*) and smaller ones of Augite (*a*) imbedded in a microlitic groundmass. The clear spaces (*c*) are cavities. (*After Fouqué and Lévy.*)

(labradorite or anorthite) and augite. When olivine is present, the rock is termed olivine-basalt. (See Fig. 105.) In addition to the augite there are often present partially fused fragments of brown mica and of hornblende. (See Fig. 105.)

Adopting a mineralogical classification, the different types of basalt may be summarized thus :—

a. Basalt proper = plagioclase + augite.
b. Olivine-basalt = plagioclase + augite + olivine.
c. Hornblende-basalt = plagioclase + augite + hornblende.

Accessory minerals present in the basalts are ilmenite and magnetic iron-ore, in black opaque grains; apatite in colourless needles; and zircon, in conspicuous red grains. Isolated and much-corroded quartz grains occur; but it is an open question whether they are indigenous to the basalt or are xenocrysts caught up during its eruption. Chlorite, calcite, and epidote, either disseminated or filling amygdaloidal cavities,

FIG. 106.

Olivine-basalt (Markle Type), Markle Quarry, Garlton Hills.
(Between crossed nicols.)
Pl. Plagioclase. *O.* Olivine.
The black specks are magnetite; the microlites, felspar. Augite is represented by decomposition products only.

occur abundantly in basalts that have undergone alteration. The chlorite is derived mainly from the decomposition of the augite; the calcite and epidote, from the felspar; while the olivines are mostly

entirely replaced by serpentine, limonite, magnetite, or carbonates of lime and magnesia. Zeolites (natrolite, phillipsite, scolecite) and agates are frequently the material composing the amygdales of the basalts.

The following are chemical analyses of typical basalts:

ANALYSES OF BASALTS.

	I. Basalt, Markle.	II. Basalt, Hailes Castle.	III. Basalt, Skye.	IV. Basalt, Kippie Law.	V. Basalt Average.
SiO_2	49·54	49·07	46·61	46·01	48·78
Al_2O_3	22·23	19·43	15·22	19·19	15·85
Fe_2O_3	9·55	10·58	3·49	5·91	5·37
FeO	1·12	2·35	7·71	6·75	6·34
MgO	2·80	4·36	8·66	6·81	6·03
CaO	7·19	7·87	10·08	8·68	8·91
Na_2O	4·56	3·31	2·43	3·27	3·18
K_2O	1·81	·98	0·67	1·20	1·63
H_2O	2·42	2·26	3·17	3·07	1·76
TiO_2	—	—	1·81	—	1·39
P_2O_5	—	—	0·10	—	0·47
MnO	·08	·32	0·13	·19	0·29
	101·30	100·53	100·08	101·08	100·00

I. Carboniferous Olivine-Basalt. — Markle Quarry, Garlton Hills, Haddingtonshire (J. S. Grant-Wilson).

II. Carboniferous Olivine-Basalt.—Hailes Castle, Garlton Hills, Haddingtonshire (J. S. Grant-Wilson).

III. Tertiary Olivine-Basalt.—Allt Fionnfhuachd, Drynoch, Skye (W. Pollard).

IV. Carboniferous Olivine-Basalt.—Kippie Law, Garlton Hills, Haddingtonshire (J. S. Grant-Wilson).

V. The average of 161 analyses of typical basalts (largely olivine-bearing): R. A. Daly, *Journ. of Geol.*, vol. xvi., 1980, p. 409.

With regard to structure, the basalts are very variable. They may contain no phenocrysts, or be crowded with large crystals of the different constituents. They may be holocrystalline or semi-vitreous. They may be very felspathic, passing then into the andesites, or nearly free from felspar, grading then into limburgites and augitites.

In one common type porphyritic olivines and augites are imbedded in a groundmass composed of lath-shaped felspars and microlitic or granular augite. Such rocks are characteristically developed on the right bank of the Rhine (Siebengebirge, etc.), and in the Midland Valley of Scotland.

In some basalts, *e.g.*, the Tertiary lavas of the west of Scotland, there is a tendency towards the ophitic structure; and in these rocks a gradual passage to the ophitic dolerites can be traced. The andesites, into which the basalts also pass by every gradation, are in general distinguished from them by an abundance of felspar phenocrysts, while augite occurs in smaller and less frequent crystals, and olivine only as a rare accessory.

Basalt occurs in "flows" or beds of great extent and variable thickness, forming characteristic plateaux and terraced hills (Snake River Plains of Oregon, the Deccan in India, the Western Isles of Scotland and the North of Ireland); also in dykes which represent, in many cases, the fissures through which the molten lava welled out. The fact that in these vast plateaux there is no thickening toward particular centres whence eruption might have been supposed to take place, and no accumulation of pyroclastic material, is

the main evidence on which the "fissure eruption" theory is based. The "bedded" basalt is slaggy and amygdaloidal on the outer surface. Where basalt has been quickly cooled, by contact with cold rock, a thin layer or selvage of black opaque glass is invariably

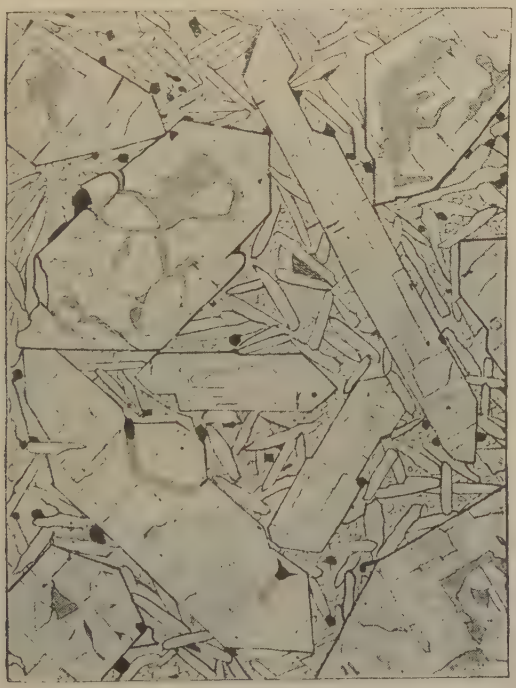

FIG. 107.

Synthetically prepared Olivine basalt. (*After Fouqué and Lévy.*)

present. This basaltic glass is known as **tachylyte**. It decomposes into a yellowish substance known as **palagonite**.

Basalt is very hard and tough, and constitutes an excellent material for paving and road-metalling. Olivine-basalt has been artificially produced by fusing the necessary ingredients, and allowing the fused mass to cool slowly. Fig. 107 shows the appearance under the microscope of a thin section of an olivine-basalt synthetically prepared by Messrs. Fouqué and Lévy.

THE ALKALI-BASALT FAMILY.

This family comprises all those basic rocks in which in addition to, or in place of, the lime-bearing plagioclase there is present either an alkali-felspar (orthoclase), or a felspathoid (nepheline, leucite or melilite). It thus corresponds to the alkali-gabbro family in the plutonic rocks.

The **tephrites** [1] and **basanites** [2] form the basic end of the felspathoid series, and only differ from the phonolites by containing plagioclase instead of orthoclase felspar. The tephrite type may be defined, therefore, as essentially composed of plagioclase, augite and either nepheline or leucite, while basanite is a similar type with the addition of olivine. In the **nepheline-, leucite-** and **melilite-basalts**, felspar is not present as an essential constituent. Otherwise the composition is similar to that of the tephrites and basanites.

The nepheline of these rocks is sometimes present

[1] Name introduced by Delamétherie and Cordier for the olivine-free plagioclase-nepheline basalts.

[2] Name introduced by A. Brongniart for the olivine-bearing variety.

in recognizable six-sided crystals; more often, however, in small disseminated granules, and then it can only be proved by chemical tests. Leucite, on the other hand, is easily known by its characteristic polygonal shape, zonal inclusions and optical behaviour. (See Fig. 108.) Melilite occurs in colourless or yellow granules, in pœcilitic plates, or in idio-

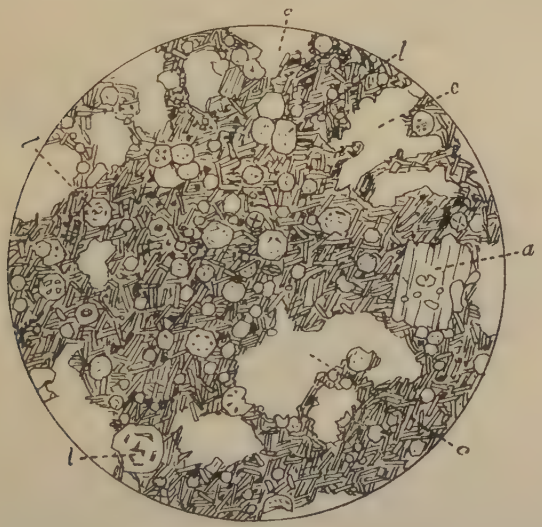

FIG. 108.

Leucite-Tephrite of Vesuvius. Crystals of Leucite (*l*) and Augite (*a*) imbedded in a microlitic groundmass. The irregular clear spaces (*c*) are cavities. (*After Fouqué and Lévy.*)

morphic crystals, giving straight extinction and low double refraction. Common accessory constituents are haüyne, nosean, melanite (black garnet) and perovskite.

The alkali-basalts may be summarized thus:

1. *Felspar* { *-nepheline* / *-leucite* } *basalts* :—

a. Tephrite = plagioclase + { nepheline / or leucite } + augite.

b. Basanite = plagioclase + { nepheline / or leucite } + augite + olivine.

2. *Basalts without felspar* :—

a. Nepheline-basalt [1] = nepheline + augite.

b. Leucite-basalt = leucite + augite.

c. Melilite-basalt = melilite + augite.

The following table gives some analyses of typical alkali-basalts.

ANALYSES OF ALKALI-BASALTS.

	I. Tephrite, Kaiserstuhl, Baden.	II. Basanite, Mount Inge, Texas.	III. Leucite-Basalt, Montana.	IV. Nepheline-Basalt, Texas.	V. Melilite-Basalt, Cape Colony.
SiO_2	50·08	48·13	47·98	40·32	36·15
Al_2O_3	18·87	18·44	13·34	9·46	15·18
Fe_2O_3	3·48	3·41	4·09	4·75	4·87
FeO	3·49	4·30	4·24	7·48	9·11
MgO	2·14	3·06	7·01	18·12	13·63
CaO	6·70	5·89	9·32	10·55	11·40
Na_2O	4·10	8·00	3·51	2·62	2·42
K_2O	4·58	3·80	5·00	1·10	1·81
H_2O	4·17	1·77	2·10	1·82	2·32
TiO_2	1·39	1·74	0·58	2·66	2·30
Other constits.	1·16	1·30	3·12	1·21	1·24
	100·16	99·84	100·29	100·09	100·43

[1] Rosenbusch (*Physiographie*, p. 1431) calls these rocks *nephelinite* and *leucitite* when they are free from olivine, but nepheline-basalt and leucite-basalt when they contain that mineral.

I. Tephrite, Mondhalde, Kaiserstuhl, Baden (F. Græff).

II. Basanite, Mount Inge, Uvalde County, Texas (W. F. Hillebrand).

III. Leucite-basalt, near Highwood Peak, Highwood Mountains, Montana (L. V. Pirsson).

IV. Nepheline-basalt, Tom Munn's Hill, Uvalde County, Texas (W. F. Hillebrand).

V. Melilite-basalt, Spiegel River, near Heidelberg, Cape Colony (J. Lewis).

THE LIMBURGITE-AUGITITE FAMILY.

The so-called **magma-basalts**[1] are rocks consisting solely of ferro-magnesian minerals and iron-

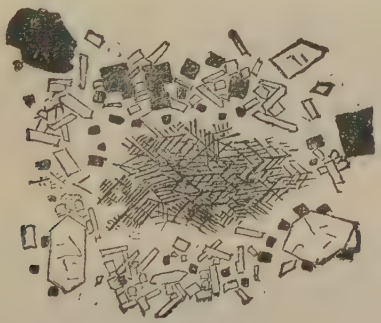

FIG. 109.

Magma-basalt, composed of crystals of Magnetite and Augite imbedded in a brown glassy base. In the centre is a patch of trichites.

ore imbedded in an abundant glassy base. Augite of the common brown type is the most abundant constituent; it occurs in prismatic crystals, giving 8-sided cross-sections, and in microlites Iron-

[1] Bořický: *Petrog. Studien an den Basaltgest. Böhmens.*

ore (magnetite) is always present, both in granules and trichites (see Fig. 86). Those rocks which, in addition to augite, contain olivine, are termed **limburgites**;[1] while those without olivine, are known as **augitites**.[2] Another type in which

FIG. 110.

Limburgite, Whitelaw Hill, Garlton Hills.
O. Olivine. *A.* Augite. *Gl.* Glassy base.

phenocrysts of hornblende occur in addition to those of augite and olivine, has been described by H. S. Washington[3] under the name of **kulaite** from Kula in Lydia.

The following table gives some analyses of typical limburgites, augitites and kulaites.

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[1] Rosenbusch: *Neues Jahrb.*, 1872, p. 35.

[2] Doelter (1882).

[3] Washington: *Amer. Journ. Sci.*, vol. xlvii., 1894, p. 144; and *Journ. of Geol.*, vol. viii., 1900, p. 44.

Analyses of Limburgites, Augitites and Kulaites.

	I. Kulaite.	II. Limburgite.	III. Augitite.	IV. Limburgite.
SiO_2	46·71	42·78	41·05	40·2
Al_2O_3	15·59	8·66	24·19	12·8
Fe_2O_3	8·27	—	9·51	4·0
FeO	1·40	17·96	—	10·4
MgO	4·90	10·06	5·11	11·9
CaO	6·41	12·29	10·99	10·4
Na_2O	4·97	2·31	5·69	2·7
K_2O	2·85	0·62	1·89	0·8
H_2O	4·24	3·96	1·62	3·4
TiO_2	2·40	·28	—	2·9
Other constits.	2·14	0·95	—	—
	99·88	99·87	100·05	99·5

I. Kulaite, Blackie Heugh, Haddingtonshire (W. Pollard).

II. Limburgite, Limburg, Kaiserstuhl, Baden (quoted from Rosenbusch's Gesteinslehre).

III. Augitite, Madeiral, São Vicente, Cape Verd Islands (Doelter).

IV. Limburgite, Whitelaw Hill, Garlton Hills, Haddingtonshire (J. H. Player).

The structure of the limburgites and augitites is usually porphyritic, the porphyritic constituents being olivine and augite. A second generation of augite microlites is very common; but the olivine is less frequently found in two generations. In

some types no porphyritic constituent was formed, and the minerals occur only as small grains and microlites embedded in a copious glassy groundmass. In such cases the rock was no doubt erupted before any portion of the magma had crystallized.

PART IV.

DISTRIBUTION OF THE IGNEOUS ROCKS AS ILLUSTRATED BY THE BRITISH ISLES.

CHAPTER I.

DISTRIBUTION OF THE PLUTONIC ROCKS

It is difficult to avoid repetition in dealing with the distribution of the plutonic rocks, for their intrusions rarely consist of a single petrographical unit. They are rather complexes of units which were, as a rule, intruded in the order of decreasing basicity. The large acid intrusions of Cornwall and Devon may appear to constitute an exception to this rule, since the earliest intrusions were already very acid; but even these comprise intrusions of slightly different composition.

DISTRIBUTION OF BRITISH GRANITES.

West of England. *Devon and Cornwall.* The five largest masses of granite in these counties have been respectively designated the Dartmoor, Brown Willy (or Bodmin Moor), St. Austell, Falmouth (or Carn Menelez), and Land's End masses. The

Scilly Islands are the highest points of a sixth large mass. Besides these larger protrusions there

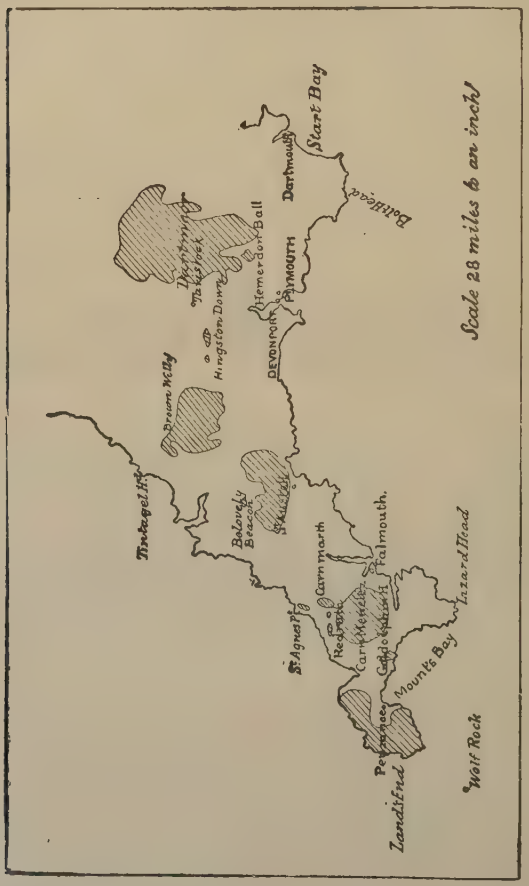


FIG. III.

Sketch-map of Cornwall and Devon, showing the chief granite-masses.

are many smaller bosses—*e.g.*, those of St. Michael's Mount, Godolphin Hills, Carn Brea and Carn Marth,

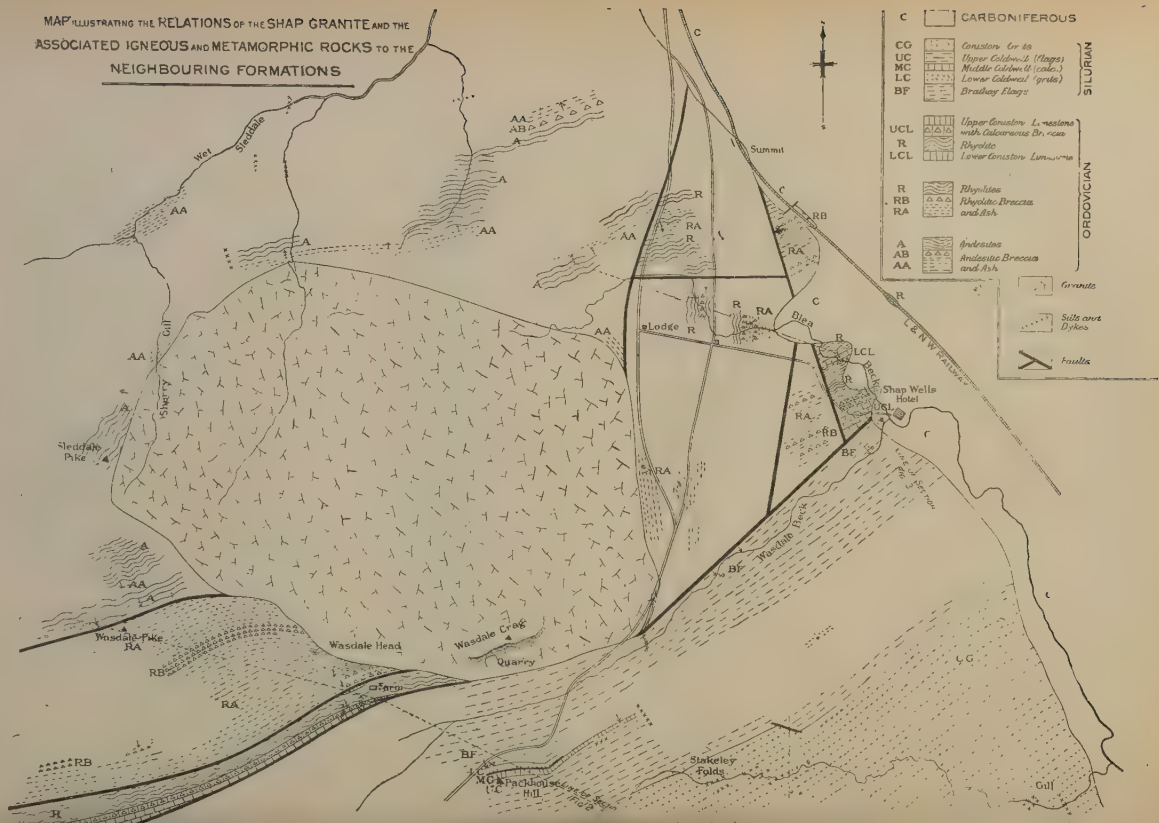
Belovely Beacon, Kit Hill and Hingston Down, and Lundy Island in the Bristol Channel. Some of these are connected, under the killas covering, with the main granite mass near which they lie (*e.g.*, at Carn Brea). Others are independent intrusions from a common magma basin. The rocks have usually a grey colour, and are porphyritic with large phenocrysts of white alkali-felspar, of which the parallel arrangement evidences flow movements in the partially consolidated magma. They belong to the alkali division of the granites, inclining rather to the potash series. (See analyses on p. 167.) A finer-grained more acid granite is occasionally found penetrating the granite-porphyry as in the Scilly Isles, on Bodmin Moor (where three such intrusions of a later granite have been observed),[1] and in the Carn Menelez mass, between Bolitho and Boswyn, and at Praze.[2]

Midland Counties. *Malvern Hills (Worcestershire).*—Gneissose granite occurs at Great Malvern (North Hill), and hornblende-granite to the north of the Wych. *Leicestershire*—At Mount Sorrel, in the Charnwood Forest, the granite contains much plagioclase, subordinate orthoclase, together with quartz, biotite and hornblende. It belongs, therefore, to the adamellite division, but appears to grade into granodiorite.

Lake District. There are three principal masses

[1] *Summary of Progress, Geol. Surv.*, 1906, p. 38, and Barrow: "The Geology of the Scilly Isles," *Mem. Geol. Surv.*, 1906, p. 4.

[2] *Summary of Progress, Geol. Surv.*, 1903, p. 25.


MAP ILLUSTRATING THE RELATIONS OF THE SHAP GRANITE AND THE ASSOCIATED IGNEOUS AND METAMORPHIC ROCKS TO THE NEIGHBOURING FORMATIONS
C CARBONIFEROUS
CG Coniston Grits
UC Upper Coldwell (flags)
MC Middle Coldwell (calc.)
LC Lower Coldwell (grits)
BF Brathay Flags
SILURIAN
UCL Upper Coniston Limestone with Calcareous Breccia
R Rhyolite
LCL Lower Coniston Limestone
R Rhyolites
RB Rhyolitic Breccia and Ash
RA
A Andesites
AB Andesitic Breccia and Ash
AA
ORDOVICIAN
Granite
Sills and Dykes
Faults
Wet Sleddale
Sherry Gill
Sleddale Pike
Wasdale Pike
Wasdale Head
Wasdale Crag
Quarry
Farm
Summit
Lodge
Blea Beck
Shap Wells Hotel
Wasdale Beck
Stakeley Folds
Packhouse Hill
Gill
L & N W RAILWAY

of granite in this district:—Shap Fells in *Westmorland*, and Skiddaw and Eskdale in *Cumberland*. The Shap rock consists of orthoclase (occurring both as large phenocrysts and in the groundmass, oligoclase, quartz, biotite and sphene. The orthoclase phenocrysts constitute about one-tenth of the rock. Excluding these, plagioclase is the dominant felspar of the ground-mass.[1] From these data it would appear that this granite belongs to the adamellite division. The Skiddaw rock is a white or grey rock, cropping out on the north-west side of Saddleback, in the Caldew valley. There it is surrounded by a contact-zone of chiastolite, andalusite, and cordierite rocks. It contains a good deal of plagioclase, but the dominant felspar is an alkali-felspar (perthite). The dominant mica is biotite, but some muscovite also occurs. The Eskdale rock is a large irregular mass extending from Wastwater and Eskdale Fell, through Eskdale and Muncaster, southwards to Bootle—an area of roughly 35 square miles. It includes a variety of types, the most usual of which is a granitic rock of coarse texture but porphyritic habit; but granophyric types also occur. The dominant felspar is perthite, although both orthoclase and oligoclase occur independently. Quartz is plentifully present, and both muscovite and biotite are constituents. The accompanying sills and dykes contain felspar phenocrysts up to two inches in length.

North Wales. The most important mass of granite is that of the Sarn district in the Lleyn

[1] Harker and Marr: *Quart. Journ. Geol. Soc.*, vol. xlvii. (1891), p. 279.

peninsula (S.W. extremity of Caernarvonshire). It is a biotite-granite, consisting of crystals of orthoclase (somewhat altered), oligoclase and biotite, with abundant granular quartz. In addition to these constituents there is a little iron-ore, apatite and zircon. It is intrusive in Ordovician slates, and builds the round hill of Mynydd Cefn Amlwch, N.W. of Sarn, and extends in an elongated patch, four miles long, by Bryn-Croes to beyond Meillionydd. See Fig. 123, p. 136. An outlier of the same rock occurs at Pyllaugiach. Most of the acid intrusives of North Wales and Anglesey, however, belong to the hypabyssal group of granophyres and microgranites, and will be referred to on p. 314.

Isle of Man. There are two important granite masses in the island, the Foxdale granite and the Dhoon granite. The former appears as the top of a hidden dome. There is a larger and a smaller exposure, separated by almost half a mile of the slate series. The intrusion was subsequent to the primary folding and crushing of the "Manx slates."[1]

The Dhoon granite appears as an ovoid patch occupying an area of about half a square mile. The intrusion apparently descends into the slates with very steep sides.[2]

From the petrographical description published by the Geological Survey, both these granites must be of the adamellite type, since plagioclase (oligoclase) appears to play quite as important a part in them as

[1] *Rep. Geol. Surv.*, 1896, p. 32.
[2] *Rep. Geol. Surv.*, 1895, p. 6.

do the alkali-felspars (orthoclase or microcline). The dominant mica is muscovite, although biotite also occurs. The Dhoon rock is more porphyritic than that of Foxdale.[1]

A third and much smaller boss consisting of grano-

FIG. 113.

Geological Map of the Isle of Man. Scale: 1 inch = 10 miles. (*After Lamplugh.*)

[1] Watts: Geology of the Isle of Man, *Mem. Geol. Surv.*, 1903, pp. 312 and 318.

diorite in association with basic rocks, occurs in the Oatland complex, near Santon.

South-West Scotland. There are three principal masses of granite intrusive in the Silurian and Ordovician rocks of Kirkcudbrightshire. They are collectively known as the Galloway granites, but may for convenience be distinguished as the *massifs* of (1) Criffel, (2) Cairnsmore of Fleet, and (3) Loch Dee. In all of them there is a considerable variation in composition, and the dominant character of each mass is different. Thus the prevailing rock in the Criffel and Loch Dee masses is a granodiorite, in which the bulk of the felspar is a lime-bearing plagioclase (oligoclase), and the alkali-felspar occurs, together with quartz, as interstitial matter.[1] In the Cairnsmore of Fleet *massif*, on the other hand, alkali-felspar (microcline) plays a more important part, and the dominant type is adamellite. The granodiorites of the Criffel and Loch Dee masses also pass, by an increase in the amount of alkali-felspar and quartz, into the adamellite type,[2] and by a decrease in the amount of quartz into tonalite or quartz-diorite; but the granodiorite and tonalite types have not been observed in the Cairnsmore of Fleet *massif*. The ferro-magnesian minerals

[1] Teall (The Silurian Rocks of Scotland, *Mem. Geol. Surv.* 1899, p. 600) writes: "The principal portion of the Criffel mass is a tonalite rather than a true granite, but in view of the fact that it is identical in general appearance with a typical grey granite, it has been considered undesirable to change the name by which it has always been known."

[2] This is especially true of the Loch Dee mass, which thus appears to occupy a position intermediate between the Criffel and Cairnsmore of Fleet masses.

are biotite and hornblende, either alone or in association. Augite also occurs. The hornblende is

FIG. 114.

Map of the Galloway District, showing the distribution of the granite complexes. Scale : 1 inch = 13½ miles.

especially abundant in the granodiorites. A clove-coloured sphene distinguishes the Criffel rock.

The variation in the composition of these granite masses is attributed by Teall to the differentiation of an original magma, rather than to the assimilation of the sediments into which the granite rocks intrude. The difference in the average composition of the three great masses is on this theory due to differentiation in a deep-seated basin; while the local differences of an individual mass are ascribed partly to the intrusion of heterogeneous magma, partly to successive intrusions of already differentiated magmas, and partly to further differentiation *in situ*.[1]

Smaller granite masses also occur in the Galloway district: at the Mull of Galloway; on the east side of the Cree, south of Creetown; Cairnsmore of Carsphairn; Spango Water; and south of New Cumnock.

All these rocks are allied in composition, and appear to belong to the same petrographical province as the larger masses above described. They are chiefly granodiorites, and are associated with tonalites and quartz-norites ("hyperite"). The contact metamorphism of the Galloway granite has been described by Miss Gardiner [2] and by Teall.[3]

South-East and Central Highlands. This district is remarkable not only for a great development of granitic rocks, but also for the remarkable range

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[1] Teall: *Mem. Geol. Surv., Scotland.* Sheet 5 (1896), 41-43; The Silurian Rocks of Scotland, *Mem. Geol. Surv.*, vol. i. (1899), p. 623; and *Rep. Geol. Surv.*, 1896, p. 43.

[2] *Quart. Journ. Geol. Soc.*, vol. xlvi. (1890), p. 569.

[3] The Silurian Rocks of Scotland, *Mem. Geol. Surv.* (1899), pp. 631-645.

in composition and variation in the mode of occurrence of the latter. The granites are broadly divisible into two: an older and a newer group, the former being in Mr. Barrow's opinion of pre-Torridonian age and the latter of post-Silurian age.[1] These two groups differ fundamentally in their mode of occurrence; for, while the newer granites occur usually in large coherent masses, the older are more commonly in comparatively small patches, in small sills permeating the invaded rocks (*injection lit par lit*), or are represented by veins of pegmatite which, near the parent granite, bulk almost as large as the rocks into which they are intruded, but diminish gradually as the parent rock is left. The area of pegmatite is in one case more than 30 miles long; its breadth, however, is usually only a few miles.

The characteristic feature of the more acid types of the older granites is their tendency to sub-division into an infinite number of small intrusions, which often permeate large areas and are largely responsible for the high degree of crystallization of the schists and gneisses into which they have been injected.

As a whole they are later than the main folding movements; although the greater part of the

[1] Boulders of some of the newer granites (*e.g.*, the Kincardineshire mass) are found in the Lower Old Red Sandstone conglomerate. (See *Summary of Progress*, *Geol. Surv.*, 1907, p. 111); but that the intrusion of granite material was continued to a later period, is shown by the fact, that, in the West Highlands, intrusions of granite (Ben Cruachan) have produced contact metamorphism in the Glencoe Volcanic Series, which has been found to be of Lower Old Red Sandstone age. (*Summary of Progress*, *Geol. Surv.*, 1905, p. 95; and *Q. J. Geol. Soc.*, vol. lxv., 1909, p. 611.)

NAIRN
FINDHORN AREA
INVERNESS
PETERHEAD
ABERDEEN
Loch Moy
Grantown
Netherly
Hill of Stob
Rothes
Dandaleith
Ben Rinnes
Dufftown
Huntly
Strichen
Belhelvie Complex
Hill of Fare
Cairn Gorm
Ben Avon
Ben Macdhui
Lochnagar
The Coils
Kincardineshire
Aboyne
Mount Battock
Glen Tilt Complex
Carn Mor
Ben Vuroch
Ben Vrackie
Pitlochry
Outer Margin of Crystallisation of the Highland Rocks Terminating at a plane of Overthrust
North Esk
South Esk
River Tummel
River Garry
River Spey
River Dee
R. Deveron
R. Don
R. Dee
Fault
Glen Shee
Ben Vrackie
Ben Vuroch
Carn Mor
Ben Rinnes
Ben Avon
Ben Macdhui
Cairn Gorm
Lochnagar
Kincardineshire
Hill of Fare
Mount Battock
Aboyne
Belhelvie Complex
Strichen
Dufftown
Huntly
Grantown
Loch Moy
Glen Tilt Complex
Pitlochry
Glen Shee
Fault
Outer Margin of Crystallisation of the Highland Rocks Terminating at a plane of Overthrust
REFERENCE
OLDER GRANITES
Biotite-gneiss A1
Cairnshee Granite A2
Muscovite-biotite-gneiss A3
Area permeated by above in small veins
Oligoclase-biotite-gneiss O1 and
Oligoclase-biotite-muscovite-gneiss O2 and
NEWER GRANITES
Basic portions of same
OLDER GABBRO INTRUSIONS
Sills from d°
GEOLOGICAL MAP OF THE CENTRAL HIGHLANDS

intrusions took place when the region was still under the influence of great earth-stresses, with the result that the material of the earlier, has often been separated from that of the later, consolidation. The latter appears either in the form of minute sills or threads of granite intruded along the divisional planes of the metamorphosed sediments, or as pegmatite in sills or veins. The granite and pegmatite sills are as a rule foliated; while the coarser vein material is more often unfoliated. Probably the intrusions took the form of sills while the district was still affected by the great earth stresses, and that of veins as these stresses gradually ceased.

Even single small intrusions show the result of magmatic differentiation. The central core is often a slightly foliated granite; on the margin a rock of a more alkaline and foliated type predominates; while the fringing veins pass into aplite. Each portion is slightly abnormal in composition, but were all parts mingled, the whole would make up a granite of normal composition. The intrusions can be separated into two great groups, by means of the dominant felspar; in the first (the alkali-granite type) alkali felspar (orthoclase and microcline) predominates; in the second (the granodiorite type) the alkali felspar is greatly subordinate to a lime-bearing plagioclase (oligoclase). The two groups may be further subdivided according to the micas present. In the following table Mr. Barrow gives a general view of the whole series of older granites.[1]

[1] Compare *Summary of Progress, Geol. Surv.*, 1902, p. 94.

ALKALI-GRANITE TYPE.	GRANODIORITE TYPE.
(A.1.) *Brown mica only present.* Biotite gneiss of Ben Vuroch, Glen Tilt, etc.	(O.1.) Oligoclase-biotite gneiss Glen Muick, Glen Doll.
(A.2.) *Biotite exceeds muscovite.* Cairnshee granite of Lower Deeside. Dyke-veins in the western area.	(O.2.) Oligoclase-biotite-muscovite gneiss. The Duchray Hill gneiss.
(A.3.) *Muscovite exceeds biotite.* Muscovite-biotite granite and gneiss of Forfar. Pegmatite veins specially abundant.	(O.3.) Oligoclase-muscovite gneiss. Present only in small amount as veins.

Not only are the newer granites far larger and more coherent than the older, but they also tend to occur in complex masses of widely varying composition.[1] Where the mutual relations of the rocks forming the complex are clear, the law of decreasing basicity has been found to hold good. The most basic is the oldest, and the most acid the youngest of the series of intrusions. Differentiation *in situ* may have taken place to a small extent; but the more acid rocks can be generally proved to be intrusive in the more basic. This rule, it should be noted, is applicable to the granite masses only; in the case of the dykes the rule may be reversed.

The most abundant constituent of the great coherent masses is a granite that contains brown mica, but no white; such as the Kincardineshire mass, Cairngorm, Ben Avon, Hill of Fare, Peterhead, and

[1] Compare Teall's description of the Garabal Hill Complex. *Quart. Journ. Geol. Soc.*, vol. xlviii., 1892, p. 104.

Glen Tilt. The Kincardineshire mass is the least variable, and it contains the largest amount of plagioclase (oligoclase), and biotite; but according to Mr. Barrow the plagioclase is not largely in excess of orthoclase, so that the rock must be referred to the adamellite rather than to the granodiorite division. A feature of this intrusion are the apophyses thrown out on its south-western margin. These rapidly pass to quartz-porphyries, in which there is no porphyritic orthoclase, showing that this mineral was the last to separate out. The granites of the Hill of Fare and of Peterhead have a slightly higher silica percentage than the Kincardineshire mass; while the Ben Avon and Cairngorm, the Lochnagar and the Glen Tilt masses, are the most acid of all.

A feature of these granites is the frequent occurrence on one side or the other of more or less complex masses of slightly older and more basic material (diorite, etc.), into which the granite often sends veins. This is well illustrated by the Glen Tilt mass, which has a dioritic complex on its southern and eastern margins. A similar phenomenon is seen on the eastern margin of the Lochnagar mass, on both sides of the Dee.

Besides the occurrences mentioned above there are, further north, several intrusions of the newer granites, for instance, that of Ben Rinnes in Elginshire, and Loch Moy [1] in the Findhorn area. North of the Moray Firth, large granitic intrusions of the

[1] *Summary of Progress, Geol. Surv.*, 1904, p. 82.

same age occur at Ben Loyal, Strath Halladale, Ord of Caithness, and Strath of Fleet (Lairg). Since most of these granites contain a large proportion of plagioclase, they belong chiefly to the adamellite division, in some cases approximating even to granodiorites.

South-West Highlands. In this district there are the large intrusions of the Moor of Rannoch, Ben Cruachan, and Glen Fyne, and the somewhat smaller intrusions of Ben Nevis and Ballachulish near Loch Linnhe.

As far as can be gathered from the published descriptions of these granite complexes, many of them appear to be largely made up of a basic type of granite in which plagioclase is equal to, or even considerably in excess of orthoclase: they would therefore be referable to the adamellites, or to the granodiorites, as the case may be. Thus a common type is that which forms an important part of the Ben Cruachan mass, namely, a granodiorite with predominant plagioclase and subordinate orthoclase, together with quartz, biotite and hornblende.[1] Sometimes a basic rock is penetrated by a more acid type: thus the more acid Starav granite (adamellite) appears to be intrusive in the Ben Cruachan type (granodiorite), see Fig. 130, p. 170.[2]

Similarly the grey foliated rock consisting of quartz and oligoclase, with subordinate orthoclase, biotite and hornblende, which forms a considerable proportion of

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[1] *Summary of Progress, Geol. Surv.*, 1905, p. 99.

[2] *Summary of Progress, Geol. Surv.*, 1898, p. 79.

the Moor of Rannoch mass, is also a granodiorite although it passes near the margin into a pink granite richer in orthoclase and without hornblende (adamellite).[1]

The Ben Nevis and Ballachulish rocks are sphene-bearing granodiorites, resembling the Criffel granite.[2]

Associated with the granite masses of the South-West Highlands, are differentiation products of a still more basic type. Thus Teall and Dakyns[3] have described a complex of tonalite, diorite, hyperite (norite and hypersthene-diorite) at Meall Breac and Garabal Hill (near the head of Loch Lomond) in association with the porphyritic granite of Glen Fyne; and J. B. Hill[4] mentions that there are many small protrusions of monzonite, diorite, etc., between the granite masses of Glen Fyne and Ben Cruachan, as at Beinn Buidhe, in the neighbourhood of Kilmelfort, which are intimately related to the larger intrusions

Western Isles of Scotland. The granite rocks of the Western Isles are mainly of Tertiary age. They are divided by Harker[5] into two sub-groups, according to their acidity. In the first the percentage of silica varies from 75 to 77, and the ferro-magnesian constituent, which is sparsely represented, is biotite. This type occurs at St. Kilda, at Beinn an Dubhaich in Skye, and constitutes the main mass of Arran. (It

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[1] *Summary of Progress, Geol. Surv.*, 1906, p. 80.

[2] Teall: *Report Geol. Surv.*, 1896, p. 21.

[3] *Quart. Journ. Geol. Soc.*, vol. xlviii. (1892), p. 104.

[4] *Quart. Journ. Geol. Soc.*, vol. lv. (1899), p. 478.

[5] Harker: The Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 153.

is also represented in the Mourne Mountains of Ireland.) The second group has silica varying from 70 to 72 per cent. The ferro-magnesian constituent is more abundant, and consists of hornblende and augite. There is also a tendency towards the development of granophyric structure, especially in augite-granites. This type constitutes the mass of the Red Hills of Skye. It occurs also in Mull, and in Rum (Orval). The Ross of Mull granite appears to be of newer Palæozoic age.[1] It is a type characterized by the presence of microcline-perthite. The Goatfell granite in Arran is a similar rock.

South-East Ireland.—The largest mass of granite in the British Isles is that of the Mount Leinster range in the south-east of Ireland. It is usually a coarse-grained rock, composed of potash-felspar (microcline), plagioclase (varying from albite to oligoclase), quartz, muscovite, and biotite. The stone, which varies considerably in texture and quality, is quarried at Killiney and elsewhere for building and paving purposes. The main intrusion is an alkali-granite, in which potash dominates over soda; but in some of the subsidiary intrusions, which are doubtless differential products of the same great magma basin, soda predominates; thus a soda-granite occurs at Aughrim.[2] (See Fig. 116 and analysis on p. 167.) Another forms the summit of Croghan Kinshela. (See Fig. 116 and analysis on p. 167.) This consists mainly of a brilliant white soda-felspar and grey

[1] Judd: *Quart. Journ. Geol. Soc.*, vol. xxx., 1874, p. 244. See also *Summary of Progress, Geol. Surv.*, 1907, p. 66.

[2] Sollas: *Trans. Roy. Irish Acad.*, vol. xxix., p. 471.

quartz.[1] As far as the age of the intrusion of the Mount Leinster granite can be ascertained it is post-Silurian and pre-Carboniferous: the Silurian rocks are metamorphosed at the contact, while the conglomerate at the base of the Carboniferous contains

FIG. 116.

Sketch-map of S.E. of Ireland, showing the Mount Leinster granite.

boulders of the granite. The minerals of the contact-zone include andalusite, chiastolite, staurolite, garnet and mica.

[1] S. Haughton: *Trans. Roy. Irish Acad.*, vol. xxiii., 1859, p. 563.

North-East Ireland. In the north-east of Ireland there are three principal occurrences: namely, those of the Mourne Mountains, Carlingford and Newry. The Mourne Mountain granite is a rock of rather peculiar type consisting of orthoclase, albite, and green mica. It is remarkable for the idiomorphic character

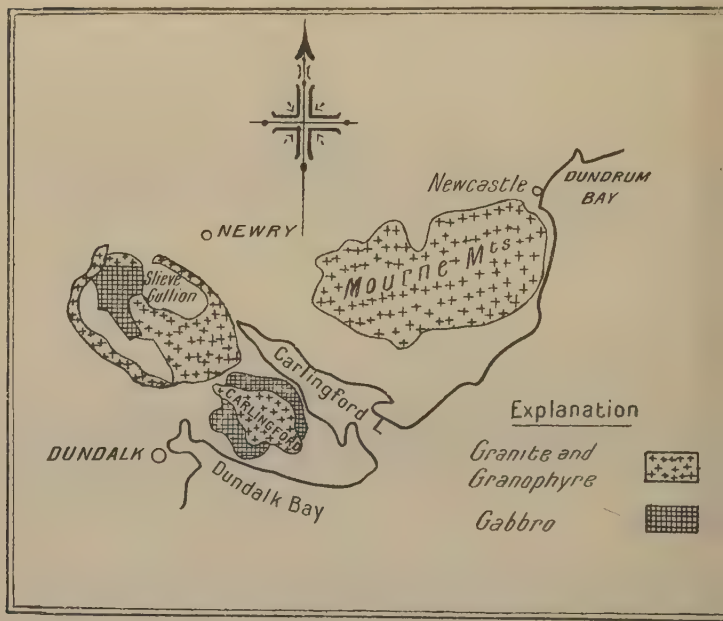

FIG. 117.

Map of the Carlingford and Mourne Mountains District, N.E. Ireland, showing the distribution of the granites and gabbros. Scale: 1 inch = 20 miles.

of its quartz and the variety of minerals found in its cavities. The age of this intrusion is certainly post-Carboniferous, and may be Tertiary. The Carlingford

rock is a granophyric granite, probably of Tertiary age. The Newry granite, which extends southward from Slieve Croob to Newry, and thence to Slieve Gullion and Forkill, is intrusive in Ordovician rocks. It includes both a potash-granite and an adamellite type, and the coloured minerals are biotite and hornblende.

North-West Ireland. In the provinces of Ulster and Connaught there are large granite complexes comprising many different types, often foliated; as examples those of Barnesbeg, Mullaghderg, Gweebara, Glenties, Barnesmore, Blacksod Bay, the Ox Mountains, Corvockbrack, Island of Omey, Leam, Roundstone, and Galway may be quoted.[1]

Channel Islands, etc. Granite with two micas occurs in the Scilly Islands; and biotite-granite is quarried in the Channel Islands, for instance, at St. Brelade in Jersey.

DISTRIBUTION OF SYENITES.

North Wales. A coarse-grained potash-syenite, consisting of large crystals of black hornblende and pink orthoclase together with subordinate quartz, augite and some accessory minerals, occurs in intrusive masses of the nature of laccoliths at Llanfaglen and Glan-y-mor, 1½ mile south-west of Caernarvon.

North-West Highlands of Scotland. Quartz-syenite (nordmarkite), syenite, and nepheline-syenite, all types belonging to the soda series, occur in the

[1] Watts: Guide to the Rock Collections, Geological Survey of Ireland, 1895, *passim*.

plutonic complex of Ledbeg, north of Loch Borolan. In this complex, which is of later date than the Cambrian, but older than the post-Cambrian movements, the chief mass, forming the hill of Cnoc-na-Sroine, is composed of soda-syenite and nordmarkite. The varieties free from quartz sometimes contain pseudomorphs after nepheline, and accessory melanite. Comparatively unaltered nepheline-syenite occurs on the north side of Cnoc-na-Sroine at the base of the hill, and on the south side of Ledbeg River. This rock is composed of nepheline and alkali-felspar (perthite) in nearly equal proportions, with a greenish biotite and melanite as accessories.[1]

Channel Islands. Syenites occur in the Channel Islands, as, for instance, at St. Helier in Jersey.

DISTRIBUTION OF MONZONITES.

North of England. Some of the augite-granites described by Teall[2] in the Cheviot Hills (*e.g.*, at Hedgehope, Linhope Burn, Staindrop Rigg) would appear to be monzonites: their silica-content is low, and they contain approximately equal proportions of a lime-bearing plagioclase (oligoclase-andesine) and alkali-felspar (perthite).

Wales. It is probable that monzonites occur among the augite-diorites of St. David's Head, some of which are reported to contain a considerable proportion of orthoclase.

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[1] Teall: Geological Structure of the North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 446.

[2] Teall: *Geol. Mag.*, 1885, p. 106.

Scotland. Monzonites occur in association with adamellite in the plutonic complexes of the South-West Highlands.[1] They have been described as occurring in many small protrusions in the neighbourhood of the granite-masses of Glen Fyne and Ben Cruachan. The rock of Eilean Balnagowan, Loch Linnhe, described by Teall[2] as a diorite containing an exceptional amount of orthoclase and possessing affinities with the syenites, must be a monzonite. They also occur in the Findhorn area (see p. 304).

DISTRIBUTION OF DIORITES.

England. Scarcely any diorites of the true plutonic type have been described as occurring in England. The so-called diorites of the Charnwood Forest and of North and South Wales are porphyrites of the Markfield type (with or without hypersthene). Those of Nuneaton are a more basic type of hypabyssal rock, and must be classed with the dolerites. In the Charnwood Forest area a type that appears to fall within the accepted definition of a diorite is the rock of Brazil Wood, near Mount Sorrel; and recently Dr. Flett[3] has described as tonalite or quartz-diorite the so-called "syenite" of Hestercomb, near Taunton in Somerset. This is a granitic to porphyritic rock, composed of oligoclase, biotite and quartz.

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[1] J. B. Hill: *Quart. Journ. Geol. Soc.*, vol. lv., 1899, p. 478, and *Summary of Progress, Geol. Surv.*, 1897, p. 48.

[2] Teall: *Rep. of Geol. Surv.*, 1896, p. 21.

[3] Flett: The Geology of the Quantock Hills, *Mem. Geol. Surv.*, 1908, p. 29.

Scotland. Diorite and tonalite are very common members of the newer granitic complexes of the Southern Uplands, and of the Eastern, Central and South-West Highlands. Most of the granite masses have, on one side or the other, complex masses in which diorite plays the chief rôle. As a rule they are slightly older than the more acid granite, since the latter sends veins into them. Glen Tilt and Lochnagar may be mentioned as examples in the Central Highlands, and Criffel, Loch Dee, and Cairnsmore of Carsphairn in the Southern Uplands. Diorites also occur in small bosses south of Glen Luce, and three miles north of Kirkcowan.[1] In the South-West Highlands a large mass of diorite is found on the south and south-eastern side of the Ben Cruachan granite, and reaches its maximum development on Ben-a-Bruidh. This rock consists of idiomorphic plagioclase, brown hornblende, biotite, and a small quantity of interstitial quartz and micropegmatite. Magnetite and apatite occur as accessories.[2] Tonalite, augite-diorite, and mica-diorite are also found in the plutonic complex on the south-east side of the Loch Fyne granite at Meall Breac and Garabal Hill, near the head of Loch Lomond.[3] Several small intrusions of basic material occur near the granite masses of Ben Nevis and Ballachulish in the neighbourhood of Loch Linnhe; for instance, the quartz-augite-diorite of Rudha Mhor, and the augite-diorite of Ardshiel

[1] *Rep. Geol. Surv.*, 1896, p. 43.

[2] *Summary of Progress, Geol. Surv.*, 1898, p. 77.

[3] Dakyns and Teall: *Quart. Journ. Geol. Soc.*, vol. xlviii., 1892. p. 104.

Hill. These rocks contain interstitial quartz and orthoclase, and are no doubt basic modifications of the granite magma.[1] There are also many intrusions of diorite or tonalite in the area south of Loch Melfort, Argyllshire, which probably are off-shoots

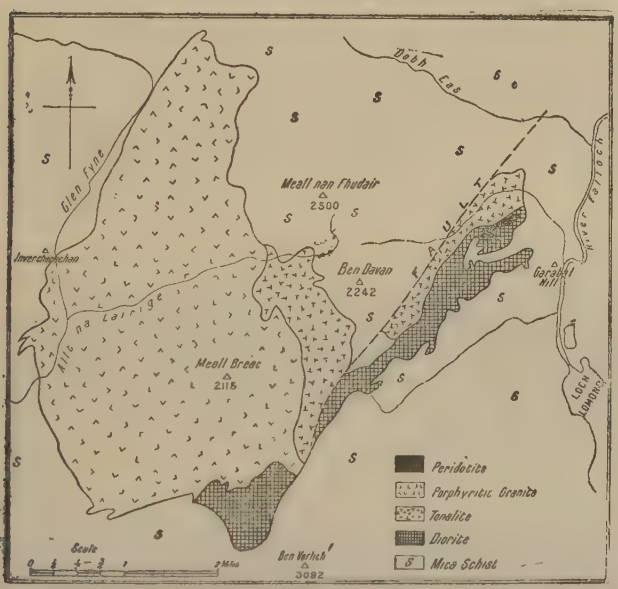

FIG. 118.

Map of the Meall Breac and Garabal Hill area, showing the Glen Fyne Granite and its associated plutonic complex. (*After Dakyns and Teall.*)

from a large underlying mass. These rocks contain plagioclase, hornblende, and biotite, with interstitial quartz and felspar.[2]

[1] Teall : *Rep. Geol. Surv.*, 1896, p. 21.

[2] Kynaston : *Summary of Progress, Geol. Surv.*, 1902, p. 80.

Masses of diorite, which do not appear to be directly associated with granitic intrusions, are also found in the Central Highlands—*e.g.*, the diorites of Glen Shee and Glen Doll. The Glen Doll complex ranges in composition from gabbro, through diorite to tonalite.

Tonalite and diorite also occur as basic modifications of the many granites in the Findhorn area; for instance, the diorite patch north and south of Tomatin, and other occurrences, in the valley of the Findhorn.[1] Diorite occurs at Netherly, Stob Hill, and Dandaleith[2] as small intrusions, which are probably genetically connected with the granite complex of Ben Rinnes. The Netherly diorite is rather coarse-grained, and consists of hornblende, biotite, greyish quartz, and felspar. The latter is mainly plagioclase, but some orthoclase is also present. In addition to these minerals there is a little grey-green pyroxene, sphene and apatite. The Dandaleith rock is a dark-coloured quartz-diorite, composed of green hornblende, plagioclase felspar, and varying amounts of quartz. Orthoclase is always present and when it becomes of equal importance with the plagioclase the rock passes into a monzonite.

Ireland. In the south-east of Ireland, diorites are intrusive in Ordovician sediments. They consist of quartz-mica-diorite or tonalite (as in the irregular boss extending from Carrigmore to West Aston, four miles east of Rathdrum), of quartz-diorite (as at Bologh Lower, three miles east of Rathdrum[3]), and

[1] *Summary of Progress*, *Geol. Surv.*, 1904, p. 83.

[2] Flett: Lower Strathspey, *Mem. Geol. Surv.*, 1902, p. 36.

[3] Hatch: *Geol. Mag.*, 1889, pp. 262, 263.

augite-diorite (as in the neighbourhood of Kilpatrick House, north of Arklow).

Channel Islands. Diorites compose the whole of the northern part of Guernsey ; and occur in Jersey in St. Aubyn and St. Clement Bays ; also in Alderney, as at Fort Touraille. These rocks often contain augite in addition to hornblende.

DISTRIBUTION OF ALKALI-GABBROS.

Although this important division of the plutonic rocks is no doubt well represented among the basic members of the igneous complexes of Scotland, very few examples have, as yet, been described.

South-West Highlands. The type occurrence of kentallenite is at Kentallen Quarry, half a mile west of the Ballachulish granite, near Loch Linnhe It is locally known as "black granite," and is remarkable for its "lustre mottling." Orthoclase and plagioclase are present in approximately equal proportions, and the remaining constituents are olivine, augite, and biotite. The silica percentage is about 48.[1] A similar rock occurs as a small boss near the head of Gleann Leac-na-Muidhe. Other intrusions of the same rock occur in Glen Creran.[2] Other intrusions of this rock have been met with near Beinn Bhuidhe (Brannie Burn, and Allt an Sithein, a tributary of the Shira River).[3] These are assigned to the same period of

[1] Teall : *Rep. Geol. Surv.*, 1896, p. 23.

[2] *Summary of Progress, Geol. Surv.*, 1904, pp. 69 and 70 ; and Hill and Kynaston, *Quart. Journ. Geol. Soc.*, vol. lvi., 1900, pp. 531-540.

[3] *Summary of Progress, Geol. Surv.*, 1899, p. 50.

intrusion as the Ben Cruachan granite, and consequently are of later date than the Lower Old Red Sandstone lavas of Argyllshire.[1]

North-West Highlands. The type locality for borolanite is north of Loch Borolan in South Assynt, where the rock occurs in the neighbourhood of the granitic mass of Cnoc-na-Sroine, near Ledbeg. Typical borolanite is found in the small burn named Allt-a'-Mhuilinn on the six-inch map of the Ordnance Survey. This burn crosses the road about one and a quarter mile east of the inn at Aultnacallagach. Outside the plutonic area of Cnoc-na-Sroine the only other place in the North-West Highlands where rocks allied to borolanite have been found is the Coigach district of West Ross-shire, where they occur as dykes intrusive in the Torridon Sandstone.[2]

DISTRIBUTION OF GABBROS.

Devon and Cornwall. Typical diallagic gabbros (with and without olivine) occur in the Lizard district (Karakclews and Coverack, Pen Voose, and Kildown near Cadgwith).[3] These rocks are much foliated in places, the augite having been replaced by fibrous hornblende (uralite or actinolite), and the felspar altered into saussurite.

Lake District. Gabbro builds a portion of Carrock Fell, north-east of Keswick, where it is

[1] Kynaston: The Geology of Mid-Argyll, *Mem. Geol. Surv.*, 1905, p. 102.

[2] Teall: Geological Structure of the North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 444. See also *Trans. Roy. Soc. Edin.*, 1892, p. 171.

[3] Teall: *Geol. Mag.*, 1886, p. 483.

associated with granophyre. The felspar of the gabbro is chiefly labradorite. The ferro-magnesian constituent is chiefly augite, but enstatite is sometimes intergrown with the augite. In one type brown mica is an abundant constituent; ilmenite predominates in marginal portions; while in the innermost portions quartz is found intergrown with felspar (in part orthoclase) as interstitial micropegmatite.[1] Another but smaller mass occurs in the Cross Fell range at Cuns Fell. This rock consists of plagioclase (labradorite to andesine) and augite, together with secondary hornblende.

North Wales. Two small bosses of gabbro break through the granite of Sarn in the Lleyn peninsula (at Craig-y-fael, two miles south-west of Sarn, and Plas Llangwnadl). Harker[2] describes these occurrences as partially amphibolized gabbro, consisting, at Craig-y-fael, of "augite and diallage, hornblende and actinolite, felspar and opaque iron-ore, with some pale-green decomposition-product which has the character of a chloritoid." The hornblende-plagioclase rocks of the Lleyn peninsula often have a gabbro-like structure as at Penarfynydd. (See p. 336.)

South Wales. A good type of gabbro or norite occurs at St. David's Head in Pembrokeshire. It contains enstatite as well as augite, and some biotite. Quartz is sparingly present. With increased silica percentage the rock passes into enstatite-diorite.[3] A

[1] Harker: *Quart. Journ. Geol. Soc.*, vol. l. (1894), p. 316.

[2] Harker: The Bala Volcanic Series of Caernarvonshire, *loc. cit.*, p. 89.

[3] J. V. Elsden: *Quart. Journ. Geol. Soc.*, vol. lxi., 1905, p. 584

diallage-gabbro with labradorite and olivine, forms the summit of Hanter Hill in Herefordshire.

South Scotland. Gabbros which closely resemble those of the Lizard district, occur in Ayrshire, in the Carrick district, at Lendalfoot, and at Colmonell.

Norites, or "hyperites"—dark-coloured, medium to coarse-grained rocks, composed of plagioclase, hypersthene, augite and biotite—form a part of the granite complexes of Loch Dee, Galloway area.[1]

Western Isles of Scotland. Some of the most rugged hills of these islands are built up of intrusive masses of gabbro. The largest area of gabbro is in Skye, where it appears as laccoliths in the Cuillin Hills, and as bosses in the Broadford district. Both olivine and olivine-free gabbros occur, and the two types are intimately associated. The felspar is usually labradorite; but bytownite and anorthite occur in the more basic types. The pyroxene is usually augite, but occasionally the rhombic pyroxene is associated with the monoclinic variety. A large proportion of the mountains of the southern half of Rum consists of basic and ultra-basic plutonic rocks. According to Harker, three partial magmas were formed by deep-seated differentiation, and intruded as laccoliths in the following order: (1) ultra-basic rocks; (2) eucrites and gabbros; (3) granites and granophyres. The ultra-basic rocks sometimes consist of dunite (olivine-rock), but a more common type is a rock consisting of olivine with some anorthite, enstatite, augite, and chromite. There are many sheets

[1] Teall: *Rep. Geol. Surv.*, 1896. p. 42.

of pale and spotted rocks composed of anorthite and olivine in practically equal proportions (allivalite). The basic rocks are principally norites or eucrites, consisting of hypersthene, augite, olivine, and anor-

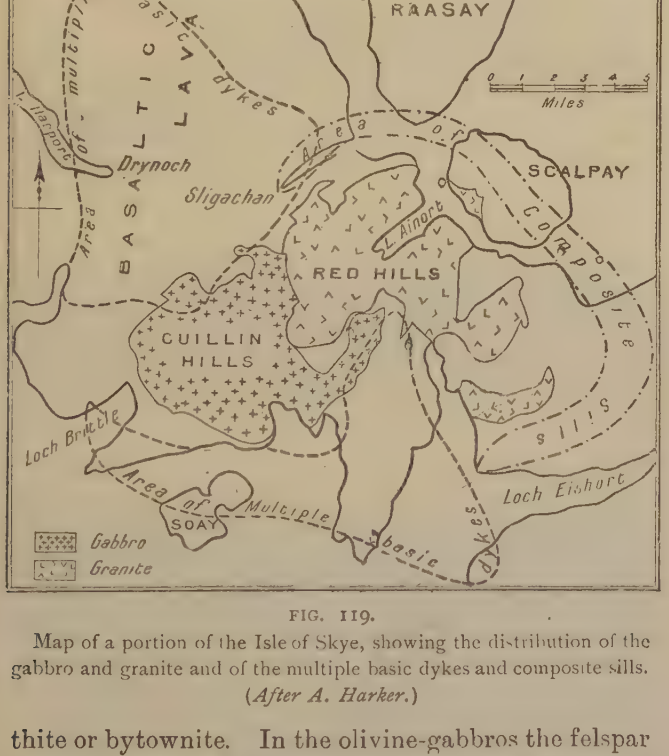

FIG. 119.

Map of a portion of the Isle of Skye, showing the distribution of the gabbro and granite and of the multiple basic dykes and composite sills. (*After A. Harker.*)

thite or bytownite. In the olivine-gabbros the felspar is labradorite, and rhombic pyroxene is uncommon.[1]

[1] Harker: The Geology of the Small Isles of Inverness-shire. *Mem. Geol. Surv.*, 1908, and *Quart. Journ. Geol. Soc.*, vol. lix., 1903, p. 208.

In Mull the gabbro occurs mainly in numerous sheets intruded into the bedded basalts. The promontory of Ardnamurchan consists largely of gabbro.

Central and Eastern Highlands. Gabbros and hornblende-gabbros (without olivine) form a great mass at Portsoy, near Banff. Another mass occurs further to the south, a little north of the Dee (Aberdeenshire). Another crops out in the fork of the rivers Dee and Muick, south-east of Balmoral; and several small bosses are exposed between this point and Glen Fernate in Perthshire. Similar small intrusive masses occur along a line drawn in a south-westerly direction from Ben Bhrackie, near Pitlochry, through Ben Lawers to the west coast.

These coarse gabbros were, in Mr. Barrow's opinion, intruded into the Highland sediments while the latter were still practically horizontal, from Loch Fyne on the west coast to Portsoy on the east coast. Their position is shown on the map on page 290. In addition to the dominant chain there are subordinate intrusions along other lines, a good example of which occurs in Glen Fernate,[1] where the gabbro cores trend north-west and south-east. In the movements that led to the present structure of the Highlands, these chains of gabbro intrusions formed, according to Mr. Barrow's view, a line of resistance against which the old Highland sediments were squeezed and folded. Although the gabbros have been involved in the crushing, numerous cores, and at times considerable masses have preserved their original granitic and ophitic structures. But the pyroxene has been

[1] Sheet 56 of the Geological Survey of Scotland.

replaced by actinolite, and the ilmenite by granular sphene or rutile. These gabbros were the feeders of a number of intrusive sills, now for the most part greatly altered to actinolite-schists, some of which are very persistent; that at the base of the Loch Tay limestone is probably the best known, though it is not the most important.

The troctolite type of gabbro is found as a basic differentiation of some of the plutonic complexes of post-Silurian age, as in the Belhelvie complex.

North-West Highlands. Rocks composed of plagioclase (labradorite) and pyroxene (hypersthene, augite) occur as bands in the fundamental complex or Lewisian gneiss of Sutherland. According as they contain garnet or not, they may be divided into a pyroxene-granulite and a gabbro or norite type. Associated with the pale-green augite is a green hornblende, and accessory biotite occurs in scales. The garnet of the pyroxene-granulites is of a deep red colour. By a diminution in the quantity of felspar the rocks pass over into pyroxenites.[1]

Ireland. Gabbros of the eucrite type occur in the Carlingford district, in association with granophyre. The micropegmatite which occurs in the more basic portions of these gabbros (as at Barnavave), is considered by Sollas to owe its origin to an injection of the gabbro by the granophyre magma.[2]

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[1] Teall: Geological Structure of the North-West Highlands. *Mem. Geol. Surv.*, 1907, p. 50.

[2] Sollas: *Trans. Roy. Irish Acad.*, vol. xxx. (1894), pp. 477-512.

CHAPTER II.

DISTRIBUTION OF THE HYPABYSSAL ROCKS.

DISTRIBUTION OF QUARTZ-PORPHYRIES.

Devon and Cornwall. Acid dykes, locally known as "elvans," are abundant in these counties. They traverse both the Devonian slates (killas) and the granite bosses, and are no doubt genetically connected with the intrusion of the latter. In petrographical character they vary from compact felsites to microgranites and porphyries, containing large crystals of felspar and quartz, such as occur near St. Hilary, at Sydney Cove, at Croft Michel near Crowan, and at Grenofen near Tavistock. Some are microcrystalline in the central part of the dyke and porphyritic near the margin (*e.g.*, the Perranporth elvan). Occasionally the chilled margins show flow structure.

Lake District. The so-called "syenite" of Buttermere, which extends from Buttermere to Ennerdale and Wastwater, is a typical granophyre. The ferromagnesian constituent of this rock is chiefly biotite, or chlorite derived from it. Augite is subordinate.[1]

[1] Rastall : *Quart. Journ. Geol. Soc.*, vol. lxii. (1906), p. 253.

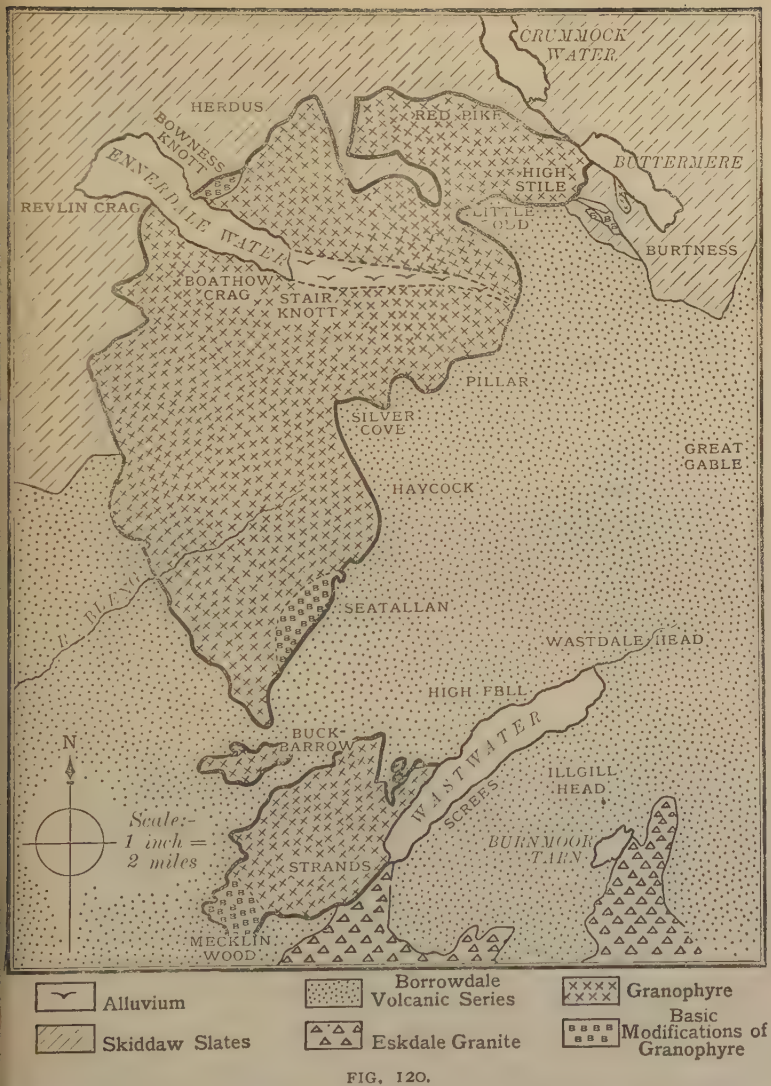

FIG. 120.

Map showing the geological relations of the Ennerdale Granophyre, Lake District. (*After R. H. Rastall.*)

The Armboth dyke is a spherulitic or granophyric quartz-porphyry, composed of bright-red. felspar (orthoclase) and dark bi-pyramidal quartz grains, scattered evenly through a dun-coloured groundmass, containing garnets. Granite-porphyry and microgranite occur as bosses and dykes: thus the two laccoliths of St. John's Vale, which are intruded at the junction of the Borrowdale volcanic series and the Skiddaw slates, and one of which is quarried near Threlkeld station, are granite-porphyries containing phenocrysts of orthoclase and small garnets; and dykes of a similar rock, with or without porphyritic crystals of quartz and felspar, occur, for instance, at the following localities:—east side of Hawes Water, Kirk Fell, Ulpha near Broughton, and Black Combe. In the Wastwater district there are innumerable dykes and sills connected with the Eskdale granite, some of which show felspar phenocrysts up to two inches in length. A remarkable granite-porphyry, containing, besides phenocrysts of a red orthoclase, plagioclase and quartz, large plates of muscovite and small flakes of biotite, occurs at Dufton Pike in the Cross Fell Inlier, and is known locally as the Dufton granite. A dyke of spherulitic felsite traverses the rocks of High Fell in Cumberland.

North Wales. Intrusive bosses of granite-porphyry, microgranite, and granophyre are abundant in Caernarvonshire, Anglesey, and Merionethshire. According to Harker,[1] the granophyres are character-

[1] The Bala Volcanic Series of Caernarvonshire, *loc. cit.*, p. 49, and Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, p. 156.

FIG. 121.

Map showing the geological relations of the Tan-y-Grisiau Granophyre, North Wales. (*After A. V. Jennings and G. J. Williams.*) *A.* Microgranite ; *B.* Tremadoc Beds ; *E.* Arenig Beds ; *K.* Llandeilo Beds.

ized by the presence of augite, while the microgranites have both this mineral and biotite. Only in two localities is the place of these minerals taken by a peculiar blue soda-hornblende (riebeckite) (Paisani type of Mynydd Mawr[1] and Bwlch Cywion). A good type of microgranite ("Nevin type" of Harker) is found at Trefor and Nant Gwrtheyrn in Yr Eifl, and at Mynydd Nevin. Microgranite (*eurite* of Messrs. Cole and Jennings)[2] forms the ridge of Cader Idris, south-west of Dolgelly, and another ridge of the same rock runs due north to the east of Rhobell Fawr (Allt Llwyd and Ddualt). At Tan-y-Grisiau, 2 miles north of Ffestiniog, there is an intrusive mass of microgranite (sometimes granophyric) 2½ miles long. The date of the intrusion was subsequent to the hardening and cleavage of the Tremadoc rocks and possibly later than the consolidation of the Llandeilo beds. The rock is characterized by abundant quartz and poorness in ferro-magnesian minerals. The felspar appears to be largely a triclinic variety, possibly soda-orthoclase.[3] Granophyres occur in Caernarvonshire in the Moel Perfedd laccolith, at Y Drosgl and Craig-dol-Owen, at Pen-y-gar (2½ miles east of Llanaelhaiarn, between Pistyll and Nevin),[4] at Llanbedrog and Mynydd-tir-y-cwmmwd.

[1] Mynydd Mawr is a boss-like mass three miles west of Snowdon. According to Harker it is probably the plug of a volcanic vent of Bala age, marking the source of some of the lavas of Snowdon, Moel Hebog and Llwyd Mawr.

[2] *Quart. Journ. Geol. Soc.*, vol. xlv., 1889, p. 422.

[3] Jennings and Williams, *Quart. Journ. Geol. Soc.*, vol. xlvii. (1891), p. 368.

[4] Harker, *loc. cit.*, p. 55.

South Wales. Spherulitic or granophyric quartz-porphyries and microgranites occur at St David's. The main mass of granophyre (Dimetian of Dr. Hicks) is probably a laccolithic intrusion in the Pebidian volcanic series. The intrusion, however, was pre-Cambrian.[1] The marginal portion of the rock is porphyritic.

A dyke of granophyre traverses the ridge of the Stanner Rock, near Old Radnor.

Isle of Man. Numerous acid dykes of pre-Carboniferous age traverse the Manx slates on the southern margin of the Foxdale granite. They consist of small phenocrysts of plagioclase, orthoclase, and hexagonal crystals of muscovite in a microcrystalline groundmass. One of them (the Crosby dyke), has been analysed, and the result shows that the soda-alkali preponderates.[2] Similar dykes occur on the west coast north of Bradda Head, and on the east coast north of Maughold Head, and these have also been traced to the Foxdale granite.

Acid dykes also spring from the eastern margin of the Dhoon granite. They have a platy structure due to shearing, and contain small grains of opalescent blue quartz.[3]

South Scotland. Quartz-porphyry dykes are abundantly developed in connection with the granitic intrusions of the Southern Uplands. They consist of

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[1] J. F. N. Green: *Quart. Journ. Geol. Soc.*, vol. lxiv., 1908, p. 363.

[2] *Quart. Journ. Geol. Soc.*, vol. xlvii., 1891, p. 439.

[3] The Geology of the Isle of Man, *Mem. Geol. Surv.*, 1903, pp. 313-315.

quartz-porphyries and microgranites, as at Dalbeattie, Castle Douglas, Carsphairn, and of felsites, as at Bennan Hill, west of Loch Ken, and at the head of Loch Doon.

A few intrusive bosses of quartz-porphyry occur in the Midland Valley. That of Tinto Hill may be quoted as an example. A riebeckite-rock of the Paisani type occurs at Ailsa Craig.[1]

South-West Highlands. An enormous number of intrusions of quartz-porphyry, associated with sills of porphyrite, occur between Loch Awe and Loch Fyne, in the Loch Awe series, of which they form a considerable proportion. They are probably connected genetically with the plutonic masses of Ben Cruachan and Garabal,[2] which they are also found traversing.

Central Highlands. Dykes, sills and small bosses of quartz-porphyry occur sporadically in the Central Highlands: thus their occurrence has been noted in the mountainous district between Braemar and Glen Ey.[3] The so-called "porphyrite" of Lintrathen in Forfarshire is a quartz-porphyry containing bipyramids of quartz and a black wide-angled potash mica, set in a groundmass of orthoclase.

Western Isles. The granophyres and microgranites of Mull, Skye, Eigg and Rum form a characteristic feature of the Tertiary volcanic geology of these islands. They occur in intrusive bosses, sills

[1] Teall: *Min. Mag.*, vol. ix., 1891, p. 219.

[2] *Rep. Geol. Surv.* for 1895, p. 25; and *Summary of Progress*, 1897, p. 86.

[3] *Rep. Geol. Surv.* for 1896, p. 19.

and dykes. Typical masses are those of Loch Ba' and Glen More in Mull. Three small bosses occur in the island of Eigg. In Rum the same rocks build the summit of Orval. In Skye they occur in the Strath Valley, at Beinn-na-Cro between Strathmore and Strathbeg, and in the southern part of the island they extend from Loch Sligachan into the heart of the Cuillin Hills. The apophyses of the larger granite masses of the Red Hills (see p. 296) are granophyres. Pitchstone in veins and dykes is also common in the Western Isles. Thus it occurs in Skye, at Glamaig, Glas Beinn Bheag in Strathbeg, and Beinn-na-Caillich; in Rum, at Orval; in Eigg, at Rudh an Tangairt near Laig, and at the harbour; in Arran, at Brodick, Corriegills, Caisteal Abhail, Tormore; and in Ardnamurchan, at Ben Hiant. At the Scuir of Eigg there is remarkable pitchstone, formerly regarded as a superficial flow which filled an ancient valley in the plateau basalts. Recent investigations appear to show that it is an intrusive sill.[1]

Ireland. Quartz-porphyries, microgranites and felsites occur as dykes in the crystalline area of Clifden, Northern Galway.[2] Pitchstones and felsites occur as dykes in the north-eastern portion of the island; *e.g.*, the pitchstone cutting the granite of the Barnesmore range in County Donegal.

Felsite dykes and sills, which were intruded at some period intermediate between the Bala group and

[1] Harker: *Quart. Journ. Geol. Soc.*, vol. lxii., 1906, p. 40.

[2] Watts: Guide to the Rock Collection, *Geol. Surv. of Ireland*, 1895, p. 53.

the Upper Old Red Sandstone occur on the coast of Waterford. These rocks often resemble agglomerate or volcanic breccia. They consist, however, of intrusive felsite crowded with innumerable fragments of black shale and various igneous rocks.[1] Chemical analysis shows that these felsites are divisible into potash, potash-soda, and soda types.[2] (See page 214.) The following examples will suffice: potash-felsite at one mile west of Great Newtown Head and at Garrarus Strand, potash-soda-felsite at Bunmahon and Annestown, soda-felsite at Knockmahon and Ballydouane.

Microgranites, quartz-porphyries, and felsites occur as marginal modifications of the Mount Leinster granite. These rocks occur as sills in the Ordovician and Silurian sediments that flank the granite *massif*. Like the granite, they are of pre-Carboniferous age. Rocks rich in soda (soda-felsites) are frequent amongst them.

DISTRIBUTION OF PORPHYRIES.

Representatives of this family are rare in the British Isles, or have escaped notice. Possibly rocks that have been classed as quartz-felsites would, if analysed, be found to have an intermediate rather than an acid composition. On the other hand, some rocks classed as porphyrite possibly contain sufficient orthoclase in addition to their plagioclase to warrant their being termed monzonite-porphyry. The "Lambstone porphyry," a sill intrusive in the Arenig rocks near Llangynog, 6 miles south-west of Caermarthen,

[1] A. Geikie: *Quart. Journ. Geol. Soc.*, vol. lvi. (1900), p. 693.
[2] Hatch: *Geol. Mag.*, 1889, p. 545.

would, from its description by Messrs. Cantrill and Thomas, appear to be a monzonite-porphyry. Set in a fine felsitic groundmass are idiomorphic crystals of orthoclase and plagioclase (oligoclase), the latter somewhat bigger than the former. There are also minute but well-shaped crystals of hornblende.[1]

DISTRIBUTION OF PORPHYRITES.

Leicestershire. Rocks that have been described as syenites and as diorites[2] occur as small intrusions in pre-Cambrian rocks at Groby, Markfield, Cliff Hill, Bawdon Castle, Bradgate, and Hammer Cliff in the Charnwood Forest. Their mode of occurrence and micro-structure show, however, that they are hypabyssal rocks. A microscopic examination of the rocks of Markfield and Groby reveals large idiomorphic crystals of plagioclase, which, although rather decomposed, plainly show their twin-striation, and green hornblende, which is partly original and partly secondary after augite, both minerals being embedded in a groundmass of micropegmatite. These rocks are dioritic granophyres. It is suggested on p. 219 to term them markfieldite, after the type occurrence at Markfield. Similar rocks are found in South Leicestershire, at Enderby, Narborough, Croft, Earls Shilton,

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[1] Cantrill and Thomas: *Quart. Journ. Geol. Soc.*, vol. lxii. (1906), p. 245.

[2] Bonney: *Quart. Journ. Geol. Soc.*, vol., xxxiii. (1877) p. 754; xxxiv. (1878), p. 199; xxxvi. (1880), p. 313; and Rutley: *Geol. Mag.*, Dec. 3, vol. iii., p. 557.

FIG. 122.

Sketch of the igneous rocks of Charnwood Forest. (*After Bonney.*)
Horizontal lines = slaty rocks (= ash beds).
Cross-hatching = igneous intrusions.

and Stony Stanton (see map on p. 322), where their mode of occurrence suggests that they are part of a buried mountain range, the peaks of which project through the Triassic plain.

North of England and South of Scotland. Some of the so-called "basalt" or "andesite" dykes of the South of Scotland must be classed with the porphyrites: *e.g.*, the Eskdale Muir and Wat Carrick dykes. The "augite-granophyre" of Carrock Fell in the Lake District is a plagioclase-augite-rock, with a small amount of orthoclase and quartz, present as micropegmatite. It is a dioritic granophyre or markfieldite. Many of the so-called quartz-dolerites of the Lake District also belong here.

Wales. Rocks of the Markfield type, but containing hypersthene in addition to augite and without hornblende, occur in both North and South Wales. In South Wales they occur near St. David's Head,[1] at Carnedd Givian, Carnedd Sleithe, Carn Perfedd, Carn Ffold, Carn Trelwyd, and Penberry Hill. In these rocks orthoclase and quartz are present in variable quantity, mainly as interstitial micropegmatite. In the Carn Trelwyd rock, however, the proportion of orthoclase is so high as to suggest a passage to monzonite-porphyrite. With decreasing silica they pass into hypersthene-dolerites (Carn Hen, Carn Llidi), in which the interstitial micropegmatite is rare or absent. In North Wales the best example of the Markfield type is the hypersthene rock of

[1] Elsden: *Quart. Journ. Geol. Soc.*, vol. lxi. (1905), p. 588, and ibid., vol. lxiv. (1908), p. 273.

Penmaenmawr, which occurs as an intrusion in Ordovician strata on the north coast of Caernarvonshire, between Conway and Bangor. This rock consists of lath-shaped plagioclase and granular to hypidiomorphic augite and hypersthene, in a groundmass of micropegmatite.

Hypersthene-porphyrites, without granophyric structure, occur at Carn Boduan, one mile south of Nevin; and at Yr Eifl, in the Lleyn Peninsula. The Carn Boduan rock consists of phenocrysts of plagioclase, augite and hypersthene, embedded in a groundmass of felspar-microlites. The Yr Eifl rock is of similar nature, but it contains brown mica in addition to the above-named constituents, and the groundmass is crypto-crystalline to micro-crystalline.

A porphyrite, described by Elsden as lime-bostonite,[1] occurs near Abercastle on the coast of Pembrokeshire, where it is intrusive in Ordovician rocks. It consists of a few felspar phenocrysts in a felspathic groundmass, the felspar being oligoclase. No ferro-magnesian minerals are visible, but chlorite and calcite, which are present in small quantities, may be derived from their decomposition.

North-West Highlands of Scotland. Porphyrites are found south of Loch Assynt, as sills in the Torridon Sandstone, on Canisp and on Suilven, and near Inchnadamff. They were intruded before the

[1] Elsden: *Quart. Journ. Geol. Soc.*, vol. lxi. (1905), p. 594. According to the classification adopted in this book the name bostonite is limited to rocks which are associated with "complementary" lamprophyres, and clearly owe their origin to differentiation.

beginning of the post-Cambrian movements, which they are found to have shared. The well-known "Canisp porphyry" may be taken as a type. It is composed of large tabular crystals of oligoclase-albite embedded in a groundmass of quartz and turbid felspar. Brick-red crystals of orthoclase are sporadic among the phenocrysts. Ægirine-augite and biotite are the ferro-magnesian constituents.

Central Highlands. Dykes and sills of porphyrite, which are genetically related to the newer granite intrusions, occur on the banks of the Garry and near Strowan. The Beinn a' Chuallaich sill, with its plagioclase phenocrysts half an inch in length, may be taken as a type. Quartz occurs in doubly terminated pyramids, and hornblende and biotite are both present.[1]

South-West Highlands. Porphyrites occur as dykes and sills in Lorne, between Loch Etive and Loch Awe. They strike, in a north-east and south-west direction, toward the granite of Ben Cruachan, which they are found likewise to traverse.[2] The type is a hornblende-porphyrite, consisting of phenocrysts of plagioclase, hornblende and biotite, in a micro- or crypto-crystalline groundmass of quartz and felspar. They appear to be connected genetically with the Ben Cruachan granite, from which they differ but little in chemical composition. Similar rocks are found further south in the Cowal district. They occur as

[1] Flett: Geology of Blair Atholl, etc., *Mem. Geol. Surv.*, 1905, p. 116.

[2] *Rep. Geol. Surv.*, 1895, p. 29, and 1896, p. 25; and *Summary of Progress*, 1897, p. 86.

sills and dykes, and probably have a genetic connection with the granitic rocks of Loch Fyne.[1]

South-West Scotland. Porphyrites occur in the Galloway district, among the dykes associated with the Criffel and Loch Dee granite masses. Plagioclase, hornblende, biotite and occasionally quartz occur as phenocrysts in a compact groundmass. The colour varies from grey to red. The microscopic structure may be crypto-crystalline, micro-pœcilitic, micropegmatitic, or even spherulitic.[2]

Midland Valley. A dioritic granophyre with hypersthene (hypersthene-markfieldite) occurs at Tillicoultry, north of the Forth. It closely resembles the Penmaenmawr rock, described on p. 324.

Ireland. Augite-porphyrites, which were intruded between the Bala beds and the Upper Old Red Sandstone, occur on the coast of Waterford, as at Knockmahon, Bunmahon, and Ballydouane Bay.[3]

On Lambay Island, off the east coast of County Dublin, an augite-porphyrite occurs as intrusions in Bala rocks at Pilot's Hill and the Flint Rock ; this, the well-known "Lambay porphyry," resembles the *porfido verde* of the ancients. It consists of a green decomposed groundmass, composed mainly of lath-shaped felspars and augite granules, but containing also calcite, epidote, chlorite and magnetite. In this

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[1] The Geology of Cowal, *Mem. Geol. Surv.*, 1897, pp. 96, 298 ; The Geology of Mid-Argyll, *Mem. Geol. Surv.*, 1905, p. 113.

[2] Teall : The Silurian Rocks of Scotland, *Mem. Geol. Surv.* (1899), p. 627.

[3] Cowper Reed : *Quart. Journ. Geol. Soc.*, vol. lvi., 1900, p. 688.

groundmass are embedded idiomorphic phenocrysts of labradorite.[1]

DISTRIBUTION OF THE MUGEARITES AND TESCHENITES.

The type locality for mugearite is in Skye at Druim na Criche, a flat ridge 2 miles north-east of Roineval and 5 miles south-south-west of Portree. It is so named from Mugeary, a crofter village lying a short distance to the south. Mugearites identical with the typical rock of Skye occur in Eigg and in Muck.[2]

Rocks of similar chemical and mineral composition occur among the Carboniferous rocks of Midlothian (*e.g.*, Whinny Hill, Arthur's Seat, and Corston Hill, 12 miles west-south-west of Edinburgh) and East Lothian. Most of them have been mapped as lavas, but it is possible that they are sills.[3]

A teschenite, described by Corstorphine[4] as an olivine-bearing analcime-diabase from a large sill in the south-east corner of Arran (Lamlash), consists of olivine, plagioclase, augite, and analcime, together with apatite and black iron-ore.

Teschenites have also been recorded by the Geological Survey among the basic intrusions in the Carboniferous rocks of Midlothian, for instance, at

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[1] Von Lasaulx: *Tschermak's Min. u. Pet. Mitth.*, 1878, p. 419; and Gardiner and Reynolds: *Quart. Journ. Geol. Soc.*, vol. liv., 1898, p. 135.

[2] Harker: Tertiary Igneous Rocks of Skye, *loc. cit.* p. 265; and Geology of the Small Isles, *Mem. Geol. Surv.*, 1908, p. 126.

[3] Flett: *Summary of Progress, Geol. Surv.*, 1907, p. 120.

[4] Corstorphine: *Min. u. Pet. Mitth.*, vol. xiv., 1895, p. 463.

Whitehouse Point, Dalmeny, near Edinburgh. The last-named occurrence is rich in analcime and brown hornblende. It also contains plagioclase, augite, and serpentinized olivine. A similar rock occurs at Wester Ochiltree, 2½ miles south-east of Linlithgow, and at Blackburn, Bathgate.[1] Other localities are Salisbury Crags; Inchcolm; Craigleith Island, North Berwick; Carcraig and Gullane Hill[2] in the Firth of Forth.

The analcime-bearing dolerite intrusions, which have recently been described by Dr. Flett as essexites, appear to belong rather to the teschenite family on account of their hypabyssal character. The occurrences mentioned are: a dyke of great thickness, intruded in the Campsie lavas, one mile north of Lennoxtown, and a sill at Lochend, near Edinburgh.[3]

The Bartestree dolerite, according to Reynolds,[4] and the Clee Hill dolerite, according to Harker,[5] contain analcime, and these should therefore be included in the teschenite family. A typical teschenite occurs at Whitwick in Leicestershire.[6]

DISTRIBUTION OF DOLERITES.

Devonshire and Cornwall. Numerous small bosses, laccoliths and sills of much-altered dolerite, locally known as greenstone, protrude through the

[1] *Summary of Progress, Geol. Surv.*, 1907, p. 54.
[2] Teall: British Petrography, 1888, p. 191.
[3] *Summary of Progress, Geol. Surv.*, 1907, p. 54.
[4] Reynolds: *Quart. Journ. Geol. Soc.*, vol. lxiv., 1908, p. 501.
[5] Harker: Petrology for Students, 1908, p. 148.
[6] Leicestershire Coalfield, *Mem. Geol. Surv.* p. 33.

Devonian slates and the Culm-measures of these counties. Thus they occur abundantly on the margin of the Dartmoor granite; in the Teign Valley, north-west of Chudleigh and north of Newton Abbot; also in the neighbourhood of Tavistock, where they swell out into large irregular and lenticular masses. Again, numerous sills are developed around Padstow Harbour; in the neighbourhood of Endellion; between Davidstow and St. Clether, north-east of Camelford; and between Liskeard and Saltash. In texture these rocks vary from very compact dolerites, as at Gurnards Head, Zennor, and Harlyn, near Padstow, to coarser ophitic rocks, as at Templeton, Cornwall; Yarner Beacon, Dartington; Ashton, Christon, and Crocombe, north-west of Chudleigh; the Botter Rock, near Hennock; Smear Ridge, near Tavistock. Mica-dolerite occurs at Saltash, near Plymouth.

Midland Counties. *Warwickshire.* Fine-grained, rather felspathic dolerites occur as sills and dykes in the Cambrian and pre-Cambrian rocks of Nuneaton, as at Hartshill, Marston Jabet, Bedworth, Atherstone, Chilvers Coton, etc. These intrusions were described as diorites by Allport[1] and Rutley; but their mode of occurrence and structure show them to be hypabyssal rocks, while their mineral composition suggests a basic rather than an intermediate type; unfortunately no analyses appear to have been made of these rocks. Under the microscope a type occurring at Griff Farm, two miles south of Nuneaton, and at

[1] Allport: *Quart. Journ. Geol. Soc.*, vol. xxxv., 1879, p. 637.

Chilvers Coton, is seen to be largely composed of lath-shaped and prismatic crystals of plagioclase. Wedged in between the felspars are patches of chlorite and calcite, which no doubt mostly represent augite. In other types hornblende plays a more prominent rôle: thus, at Marston Jabet it occurs in long idiomorphic crystals, and at Tuttle Hill in long needles visible in the hand specimen. Such types suggest affinities to the lamprophyres.[1] In the rock occurring at Atherstone and Griff Hollow the hornblende occurs in large plates ophitically enclosing the felspar laths. Such rocks may be appropriately termed hornblende-dolerite. In some occurrences pseudomorphs after olivine occur; and occasionally the increase of olivine and corresponding diminution of the felspar content, indicate affinities to hornblende-picrites.

Precisely similar rocks occur in the Malvern range, as at the Lower Wych Quarry.

Watts[2] mentions rocks of similar type as intrusive in the Archæan rocks of the Lickey, in the Shineton shales of the Wrekin, in the rocks of the Longmynd and its northern continuation at Bayston Hill, near Shrewsbury.

Olivine-dolerites, intrusive in Carboniferous strata, occur at Pouk Hill, near Walsall; Swinnerton Park, 8 miles east of Stafford; Rowley Regis, near Birmingham; Barrow Hill, west of Dudley; Tansley Hill, near Dudley; and many other places.[3] They are composed of plagioclase, brown augite, iron-

[1] Watts: *Proc. Geol. Assoc.*, vol. xv., 1897, pp. 394-396.

[2] *Loc. cit.*, p. 395.

[3] Allport: *Quart. Journ. Geol. Soc.*, vol. xxx., 1874, p. 520.

stained olivine, and iron ore, and vary in structure from granular to ophitic. Frequently the ophitic structure is developed in the central portion of the dyke or sill, while near the margin the augite assumes a granular structure.

Derbyshire. Dr. Arnold-Bemrose [1] gives the following localities for sills of olivine-dolerite in the Carboniferous Limestone of Derbyshire: Peak Forest, Potluck, Water Swallows, Tideswell Dale, New Bridge, Ible, Bonsall, High Peak Tavern, and Low Farm.

North of England. Many of the dykes which traverse the northern counties are dolerites (without olivine). The Great Whin Sill, which runs from Cross Fell to Dunstanburgh Head, a distance of about 70 miles, is a sub-ophitic dolerite, containing enstatite in places. It also contains quartz in micrographic intergrowth with felspar. At Tyne Head, and at Cauldron Snout in Teesdale, it forms a rather coarsely crystalline variety, with long blades of augite. Its age is uncertain, but it is intrusive in, and therefore later than, the Carboniferous Limestone. The Cleveland dyke, which cuts Secondary strata (Lias at Grosmont, Yorkshire) is probably an older Tertiary intrusion. It appears at the surface at intervals for a distance of ninety miles. Its groundmass consists of lath-shaped felspars, granular augite, iron-ore and interstitial matter, and contains phenocrysts of labradorite. It is, therefore, a porphyritic dolerite. The Acklington dyke, which runs from

[1] *Quart. Journ. Geol. Soc.*, vol. lxiii. (1907), p. 278.

Bondicar, on the coast of Northumberland, into the Cheviot district, is a rock of the same type. Other well-known dykes occur in Durham and Northumberland: Tudhoe and Hett; Hebburn; Tynemouth and Coley Hill (with large porphyritic crystals of anorthite); High Green, Seaton, and Hartley. These may all be classed as dolerites without olivine. A dyke of olivine-dolerite occurs, however, near Morpeth.[1]

Lake District. Dolerites are not quite so abundant in the Cumbrian as in the Cambrian areas. The sills are best developed south of the Borrowdale Fells (in Langstrath, on Stonethwaite Fells, and crossing Greenup Gill to Ullscarf). A well-marked boss is formed by the dolerite of Castle Head, near Keswick. Similar rocks occur at Wythop Fells; and at Swirrel Edge, near the summit of Helvellyn.

Shropshire, Montgomeryshire, Radnorshire, Herefordshire, and Worcestershire. Basic intrusions of at least two ages occur in these counties: namely, those that pierce Cambrian, Ordovician, and the lowest beds of the Silurian formations, and those that pierce the Old Red Sandstone and Carboniferous formations. The latter contain olivine, while as a rule the former are free from that mineral.

Hypersthene-dolerites of the older series are intrusive in the Longmyndian sediments at Ratlinghope. They are coarse-grained and ophitic, and do not contain olivine. The Ordovician beds of the Shelve area (10 miles west of Church Stretton) are

[1] Teall: *Quart. Journ. Geol. Soc.*, vol. xl. (1884), p. 209.

pierced by a vast number of intrusive dykes and sills of this rock. They are of post-Llandovery age.[1] At Corndon and at Pitchfolds the laccolithic character of these sills can be seen. At the former locality the main intrusion rests conformably on the bedding planes of altered Hope shales, and has arched up the overlying Stapeley ash-beds.[2] In the Breidden Hills (12 miles west of Shrewsbury), hypersthene-dolerites containing both hypersthene and augite, and often with ophitic structure, occur at Rodney Pillar, Criggon, Belau Bank, and Trewern. According to Watts[3] they are probably of post-Silurian age. The dolerites of the Carneddau range, near Builth in south-west Radnorshire, cut Ordovician (Llandeilo) rocks, but are not found piercing the Llandovery beds; they are therefore considered by Woods[4] to be of post-Llandeilo and pre-Silurian age. Mica-dolerites have been described from Stanner and Hanter Hill, near Old Radnor. A distinct type occurs, as sills in the Cambrian beds of the Malvern range, on the borders of Herefordshire and Worcestershire. These rocks are ophitic and porphyritic olivine-dolerites. According to Groom[5] their intrusion took place after the deposition of the Tremadoc beds, and before that of the Upper May Hill Sandstone (Llandovery).

Younger olivine-dolerites are intrusive in the Old Red Sandstone at Bartestree, near Hereford, and at

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[1] Watts : *Proc. Geol. Assoc.*, vol. xiii., 1893-94, p. 297.

[2] Watts : *Rep. Brit. Assoc.*, 1886, p. 670.

[3] Watts : *Quart. Journ. Geol. Soc.*, vol. xli. (1885), p. 537.

[4] H. Woods : *Quart. Journ. Geol. Soc.*, vol. l. (1894), p. 587.

[5] Groom : *Quart. Journ. Geol. Soc.*, vol. lvii. (1901), p. 183.

Brock Hill, near Shelsley Beauchamp in Worcestershire. They are probably of post-Carboniferous age. The Bartestree dyke, which has a thickness of 35 feet, is a multiple dyke made up of successive injections of basic material. It strikes in an east-north-east direction through Old Red marls and sandstones, which are strongly metamorphosed by it for ten feet from the contact.[1] (See also p. 328.)

Post-Carboniferous olivine-dolerites occur, as intrusive sheets in the Coal measures, at the Clee Hills, five miles north-east of Ludlow; and a few miles further to the north-east at Kinlet, near the Wrekin, they are intrusive in the Millstone Grit and Carboniferous Limestone. There, in common with many other dolerites intrusive in Carboniferous rocks described by Allport,[2] they contain idiomorphic plagioclase, brown augite, olivine, and abundant iron-ore. Portions of both the Bartestree and the Clee Hill intrusions contain analcime, a fact which indicates a relationship to the teschenites.

North Wales. The dolerites in the Ordovician rocks of Caernarvonshire and Merionethshire occur usually in the form of sheets (sills), intruded along the bedding planes; but occasionally they swell out to irregular or lenticular masses (bosses and laccoliths). In composition they are chiefly ophitic plagioclase-augite rocks, containing no olivine, but with much secondary hornblende, chlorite, calcite and epidote.

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[1] Reynolds: *Quart. Journ. Geol. Soc.*, vol. lxiv., 1908, p. 501.
[2] Allport: *Quart. Journ. Geol. Soc.*, vol. xxx. (1874), p. 529.

A good representative of the Caernarvonshire dolerites is the "Gimlet Rock," which is quarried for paving-setts and road-metal, at Pwllheli in the Lleyn peninsula. In Merionethshire the dolerite intrusions are especially developed in the neighbourhood of Dolgelly. Thus, the mass forming the ridge of Mynydd-y-gader, north of Cader Idris, consists of a medium-grained ophitic dolerite. A similar rock occurs at Bwlchau-yr-Figen, three miles north-west of Dinas Mowddwy. A more granitoid type is developed at Bwlch-yr-Hendref, near Capel Arthog, six miles south-west of Dolgelly.

A hornblendic type is represented in the Lleyn peninsula. These hornblende-dolerites are composed of brown hornblende in ophitic plates moulding plagioclase felspar, together with a pale augite and iron ores. Olivine, partially altered to serpentine, occurs as an accessory constituent. In the Lleyn they constitute three oval masses (laccoliths ?), two of which build the hills Mynydd Penarfynydd,[1] Careg-llefain and Mynydd-y-graig, the third lying to the east of Rhiw. The Penarfynydd rock, though coarse-grained, presents a marked ophitic structure. Besides the Ordovician intrusions, certain dolerite dykes occurring in the Lleyn and in Anglesey (Menai) are considered by Harker to be of post-Carboniferous age.[2]

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[1] Underlying the hornblende-dolerite is the beautiful hornblende-picrite of Mynydd Penarfynydd.

[2] Harker: *Geol. Mag.*, 1887, p. 409, and 1888, p. 267. See also a discussion of the age of the Llyn Padarn dykes by J. V. Elsden: *Quart. Journ. Geol. Soc.*, vol.: lx. (1904), p. 372.

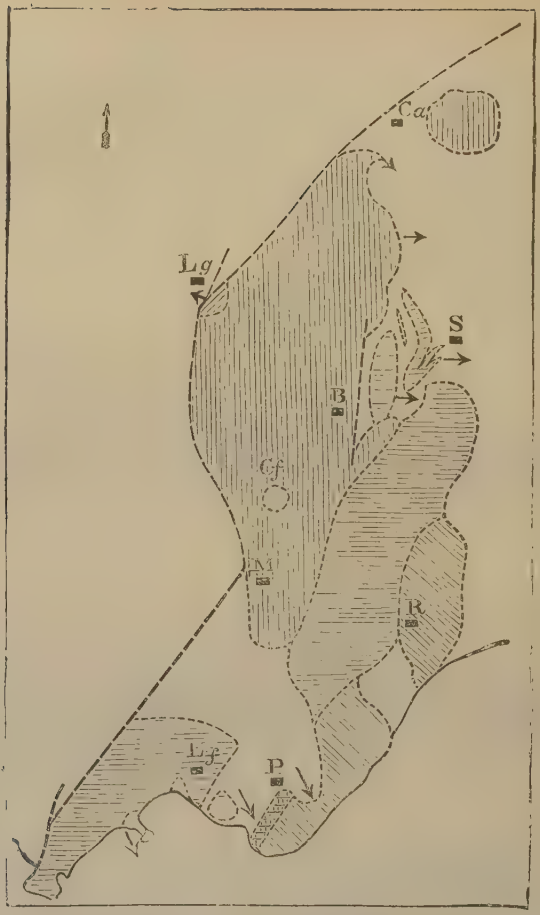

FIG. 123. Sketch-map of the Sarn District.

Granite. Dolerite. Hornblende-picrite.

Gabbro and Diorite. Hornblende-dolerite. Dips.

Probable faults marked — — — — —.

NAMES OF PLACES.

B. Bryn-croes. M. Meillionydd. P. Penarfynydd. S. Sarn.
R. Rhiw. Cf. Craig-y-fael.

South Wales. Numerous sills and bosses of dolerite occur in the Ordovician rocks of Pembrokeshire, along the coast, from St. David's Head to Strumble Head. These sills run out to sea in great numbers, in many cases forming headlands and promontories. A larger mass of typical ophitic dolerite, without olivine, occurs near Llanwnda, 2 miles north-west of Fishguard. Between Fishguard and Newport the sills are greatly developed. They run north-east and south-west, parallel to the strike of the rocks into which they are intrusive, and are continued in a southerly direction into the heart of Pembrokeshire.[1]

Hypersthene-dolerites, containing labradorite, both monoclinic and rhombic pyroxenes, a little biotite and abundant ilmenite, have been described by Elsden[2] (as biotite-norite) from several localities near St. David's Head.

Isle of Man. Numerous dykes and small bosses of altered dolerite occur in the Manx slates. They are earlier than the acid intrusions (*e.g.*, those of the Dhoon granite), by which they are cut. Newer (Tertiary ?) olivine-dolerite dykes occur at many places on the coast, as on the southern side of Maughold Head. They are especially numerous in the Carboniferous rocks of the southern part of the island.[3]

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[1] See descriptions by Cowper Reed (*Quart. Journ. Geol. Soc.*, vol. xli., 1895, p. 149), and Elsden (*ibid.* vol. lxi., 1905, p. 579, and vol. lxiv., 1908, p. 273).

[2] Elsden : *Quart. Journ. Geol. Soc.*, vol. lxiv. (1908), p. 278.

[3] Lamplugh : The Geology of the Isle of Man, *Mem. Geol. Surv.* (1903), p. 327.

Midland Valley of Scotland. Numerous intrusions of dolerite occur as bosses, sills, and dykes in the Carboniferous rocks of the Midland Valley of Scotland. They are especially numerous in Midlothian and Linlithgowshire, in the neighbourhood of Edinburgh (Heriot Mount, the Dasses, etc.), and to the west and north-west of that town (Corstorphine Hill, Dalmahoy Hill, Ratho, Cramond, and Craigie Hill), and in Fifeshire (Burntisland, Cleish Hills, and near Ceres). These rocks are remarkable for a variety of composition and structure, depending on the nature of the phenocrysts and the relation of the latter to the groundmass. A prime division is into olivine and olivine-free dolerites. The latter generally contain quartz in the form of interstitial micropegmatite. In the following classification,[1] according to structure, the first three are olivine-free types, and the last an olivine-bearing type:

(*a*) *The Ratho Type.* Plagioclase and augite in subophitic intergrowth, with a small amount of interstitial micropegmatite. Idiomorphic hypersthene is frequently present. Examples: Ratho, 8 miles west of Edinburgh; Glenboig, near Glasgow; and Stirling Castle.

(*b*) *Bowden Hill Type.* Plagioclase and augite in subophitic intergrowth, but with occasional large patches of groundmass, in contact with which the augite is idiomorphic. Idiomorphic hypersthene is also present. There is more interstitial micropegmatite than in the

[1] Hatch: *Rep. of the Geol. Surv.*, 1896, p. 64, *and* The Geology of Central and Western Fife, *Mem. Geol. Surv.*, 1900, p. 81.

Ratho type. Examples: Bowden Hill in Linlithgowshire, and the sill running northward from North Queensferry.

(*c*) *Tholeiite Type.* Felspar phenocrysts, inconspicuous and small. Mainly a mesh of fine felspar laths or microlites with granular augite, magnetite and unindividualised matter. This type occurs in the chilled margins of sills, and as small dykes.

(*d*) *Gallaston Type.*[1] Phenocrysts of olivine in

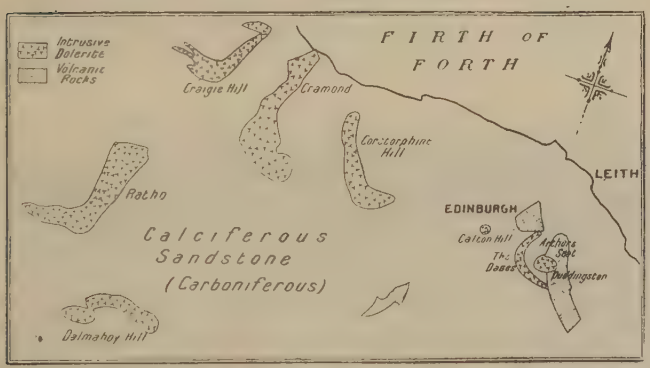

FIG. 124.

Map showing Distribution of Intrusive Dolerites in the neighbourhood of Edinburgh. Scale 1 inch=4 miles.

a sub-ophitic groundmass of plagioclase and augite. Example: Gallaston quarry at Kirkcaldy.

Olivine-dolerites occur in Forfarshire (south of Glamis) and in Roxburghshire (Dunian and Black Law). They also form a part of Corstorphine Hill and Dalmahoy Hill, near Edinburgh.

[1] Compare the Jedburgh and Kilsyth types of basalt described on pages 377 and 378.

Western Isles of Scotland. Ophitic olivine-dolerites of Tertiary age are intrusive mainly as sills between the bedding planes of the Tertiary basic lavas, and of the Jurassic strata, of Skye, Mull, and the small islands lying to the south of Skye: Rum, Eigg, Muck, etc. They are also represented on the mainland, especially in Ardnamurchan in Argyllshire.

South-West Scotland. Ophitic dolerites and epidiorites occur as intrusions in Ordovician rocks on the Ayrshire coast near Ballantrae.

South-West Highlands. — Numerous sills of "epidiorite" or dolerites, in which the augite has been changed to hornblende, extend over a tract of country, some 5 miles in breadth, through Argyllshire —for example, between the Pass of Brander and the main road from Taycreggan to Glenhaut; in the neighbourhood of Loch Awe; and in the Kilmartin district. They also occur as well-marked dykes, filling fissures in the quartzite of the Isles of Scarba and Lunga. While the sills have been folded and cleaved with the sediments into which they are intruded, the dykes have escaped a part of the folding movement, and therefore are of slightly later date. They are cut, however, by the porphyrite and lamprophyre dykes, and by the Tertiary dolerites.[1] The most prevalent type is a felspar-hornblende-schist with scattered phenocrysts of plagioclase felspar, but every gradation exists from a coarse dolerite type to the finest-grained schist.[2] Besides plagioclase and green horn-

[1] *Summary of Progress, Geol. Surv*, 1902, p. 75.

[2] J. B. Hill: *Summary of Progress, Geol. Surv.*, 1900, p. 41.

blende, the rocks contain chlorite, a pale greenish biotite, epidote, leucoxene after titaniferous iron-ore, and carbonates.

North-West Highlands. Dolerite, partly altered to epidiorite and to hornblende-schist, occurs in numberless dykes, having a north-west and south-east strike, in the Lewisian gneiss between Loch Laxford and Enard Bay. The dyke-like character of the intrusions is obvious, but in the southern area, between Loch Maree and the Islands of Rona and Raasay, it is not so apparent, although even there the evidence for the intrusive nature of the basic rocks is not wanting.[1] They are dark in colour, and medium to coarse in grain. The structure is hypidiomorphic-granular rather than ophitic, although occasionally lath-shaped crystals of labradorite may be observed penetrating grains of augite. Amongst them are enstatite- and hornblende-dolerites, besides the usual type in which augite is the dominant ferro-magnesian constituent. Olivine is in most cases absent.

South-East of Ireland. Dolerites passing into epidiorites are intrusive in the Ordovician rocks of County Wicklow (*e.g.*, at Arklow Head and in the Aughrim Valley).[2] In the east of Waterford there are numerous intrusions of dolerite dykes and sills of pre-Upper Old Red Sandstone age. Some show true ophitic structure, as at Tramore Bay; in others the ophitic structure is less developed, as at Little Island, Great Newtown Head; while in yet a third division

[1] The Geological Structure of the North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 89.

[2] Hatch: *Geol. Mag.*, 1889, p. 261.

the structure is allotriomorphic-granular, as at Garrarus, Tramore.[1]

North-East of Ireland. Tertiary dolerites occur in the basalt plateau of Antrim (*e.g.*, at Portrush; Scawt Hill, 4 miles south-south-east of Glenarm; and at Fair Head).

DISTRIBUTION OF APLITES.

As the most acid differentiation product of the granite magma, aplites are invariably associated with granite occurrences. It will therefore suffice to give a few examples.

Devon and Cornwall. Dykes of aplite occur in Devonshire in connection with the Dartmoor granite. Thus at Meldon there is an aplite dyke, containing accessory topaz and a pale-coloured tourmaline. Other occurrences on Dartmoor are at Row Tor and Scarey Tor. The Cornish granites are also frequently varied with aplite. They are especially numerous in the central portion of the Carn Menelez mass. Green tourmaline characterises an aplite vein at Lanner.[2]

Wales. Veins of soda-aplite penetrate the dioritic granophyre of Carn Llidi at St. David's Head. This type is composed mainly of albite felspar.[3]

Scotland. Aplite veins are found, in association with lamprophyres, in the neighbourhood of the Criffel and Loch Dee granites in south-west Scotland.[4] They

[1] Cowper Reed: *Quart. Journ. Geol. Soc.*, vol. lvi., 1900, p. 684.

[2] *Summary of Progress, Geol. Surv.*, 1903, p. 26.

[3] Elsden: *Quart. Journ. Geol. Soc.*, vol. lxiv., 1908, p. 284.

[4] *Rep. Geol. Surv.*, 1896, p. 44.

also occur in the Cairnsmore of Fleet mass, and are there thickly studded with small garnets.[1] An occurrence of malchite or diorite-aplite has been recorded, by the Geological Survey, in Glen Finnan, Inverness-shire. It is a grey, fine-grained rock, composed essentially of plagioclase and hornblende, but containing also a little quartz, orthoclase, and biotite. The microscopic structure is panidiomorphic.[2]

Ireland. Veins and dykes of a white, fine-grained garnetiferous aplite traverse the Mount Leinster granite. They can be well seen in the quarries on Killiney Hill, and in the railway cuttings below.

DISTRIBUTION OF PEGMATITES.

Cornwall. In Cornwall and in the Scilly Isles pegmatites are found penetrating the granite or the adjacent killas. At Tresayes Downs in the St. Austell district there is a vein of very coarse pegmatite, 150 feet wide, in the killas, a few yards from the granite margin. It consists mainly of orthoclase felspar, with some quartz, white mica, tourmaline, and fluorspar. Occasionally the mica predominates. Thus, on St. Denis Downs there is a vein of dark mica associated with a graphic aggregate of quartz and felspar.[3]

Scotland. Pegmatites are also associated with aplites in many of the south of Scotland granite areas; and fine-grained aplites even appear to pass in some cases into coarse-grained pegmatitic rocks

[1] Miss Gardiner: *Quart. Journ. Geol. Soc.*, vol. xlvi., 1890. p 569.

[2] Flett: *Summary of Progress, Geol. Surv.*, 1901, p. 70.

[3] *Summary of Progress, Geol. Surv.*, 1906, p. 37.

with graphic structure, as at Knocknairling Hill in the Galloway district.[1] A similar association of fine-grained aplite and coarse-grained pegmatite may be seen in Cornwall, as at Trewavas Head.[2]

Pegmatites of intrusive origin are abundant in many portions of the Lewisian gneiss; for instance, in the neighbourhood of Laxford, where they occur in association with granites with which they are no doubt genetically connected. The commonest type is one in which microcline and quartz are associated with pronounced graphic structure. When foliated, the microcline individuals form "eyes." A good example of this structure occurs near Shieldaig on the south side of Loch Torridon.[3] In the Central Highlands veins of pegmatite and aplite fringe the granitic areas, and Barrow has explained their occurrence as due to a squeezing out, under pressure, of the residual granite magma.[4]

DISTRIBUTION OF BOSTONITES.

Scotland The pale-brown coloured dykes, described by the Geological Survey as trachytes, which are associated with camptonites in the Cowal district of Argyllshire,[5] belong probably to the bostonite family. The following are the localities

[1] Miss Gardiner: *Quart. Journ. Geol. Soc.*, vol. xlvi. (1890), p. 569.

[2] Teall: The Silurian Rocks of Scotland, *Mem. Geol. Surv.*, (1899), p. 62.

[3] North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 258.

[4] Barrow: *Quart. Journ. Geol. Soc.*, vol. xlix. (1893), pp. 330-386.

[5] Geology of Cowal, *Mem. Geol. Surv.*, 1897, p. 166.

mentioned: Cruach Mhor, Craigendaive, Dum Mor, and Dunans. Some of these dykes have a glassy selvage in which spherulitic structure is occasionally developed. The central, well-crystallised portion consists of small lath-shaped crystals of orthoclase, together with scales of brown mica and a few prisms of pale augite. For chemical analysis see page 231.

A series of pale-coloured felsites, which occur associated with lamprophyres in innumerable sills and dykes of post-Cambrian age in the Assynt district, belong to this division of the differentiated dyke rocks. Their distribution is well shown in the one-inch sheets, 101 and 107, of the Geological Survey, and Inchnadamff is a convenient centre for their examination. A typical example occurring on the north shoulder of Cnoc an Droighinn, one mile north-east of the hotel, consists of phenocrysts of alkali-felspar (cryptoperthite) in a felspathic matrix crowded with acicular microlites of ægirine. There is thus a resemblance to Brögger's typical grorudite. Another example, but with less ægirine, and therefore more resembling Brögger's lindöite, occurs at Sgonnan Mor.[1] These rocks contain a fairly high percentage of silica, and must therefore be termed quartz-bostonites. An occurrence of bostonite also in association with lamprophyres, has been described by Flett in the Orkney Islands.[2] For chemical analysis see page 231.

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[1] Teall: Geological Structure North-West Highlands, *Mem. Geol. Surv.*, 1907, pp. 449 and 450. See also *Geol. Mag.*, 1900, p. 391.

[2] *Trans. Roy. Soc. Edin.*, vol. xxxix. (1900), p. 887.

DISTRIBUTION OF THE LAMPROPHYRES.

North of England. The North Country lamprophyres occur as small intrusions (chiefly narrow dykes) over an area extending from Teesdale to Furness, and from Bassenthwaite to Ingleton, a circular area having a diameter of 50 miles. In the centre of this area lies the Shap granite, and in consequence of the common age of the intrusions (post-Silurian but pre-Carboniferous), and the radial grouping of the dykes, a genetic connection between the granite and the lamprophyre dykes has been urged by Messrs. Harker and Marr.[1] It would appear as if the lamprophyres were a special basal modification of the granite magma, in which, with a greatly diminished percentage of silica, the total alkalies remain unchanged, while the potash is increased at the expense of the soda.[2] It has been noticed that the basic patches in the Shap granite bear a strong resemblance to some of the lamprophyres. Associated with the basic dykes are acid intrusions (aplites, etc.) which belong to a slightly earlier period of intrusion, as they are cut by the lamprophyres. In composition they belong to the group of mica-lamprophyres, being in part minettes, in part kersantites: but the distinction is not easy to make, on account of the felspar being mainly confined to the groundmass and obscured by secondary products.

The following are some occurrences that have

[1] Harker and Marr: *Quart. Journ. Geol. Soc.*, vol. xlvii. (1891), p. 285.

[2] Harker: *Geol. Mag.*, 1892, p. 199.

been described in the Sedbergh district;[1] Cross Haw Beck; railway cutting, Windermere; Kendal road; railway, Docker Garth; south of Haygarth; Helm Gill; Taith's Gill; in the Rawthey, at Ward's Intake; in Backside Beck; Holbeck Gill; Uldale Head; Watley Gill; and Westerdale. There are several localities in the Cross Fell range, of which Crowdundle Beck, and Swindale Beck may be quoted as examples. Lamprophyres of a variable composition occur also in the Lower Palæozoic inliers of Ingleton and Teesdale.

Devon and Cornwall. In Cornwall there is a dyke of minette at Trelissick Creek near Falmouth, and one of kersantite between Rosecreage Beacon and Watergate Bay on the west coast. One of a group of mica-lamprophyres occurring between Newquay and Holywell Bay, contains, in addition to large plates of dark brown mica, crystals of pale-green augite and dark-brown hornblende, in a matrix of panidiomorphic felspar and interstitial quartz.[2] Excellent examples of mica-lamprophyre occur in Devonshire, at Rose Ash, and in other localities.

Isle of Man. Lamprophyres, both the hornblende and mica varieties, occur in numerous dykes traversing the Manx slates. They are of pre-Carboniferous age. Although they also occur inland, they are mostly known in the cliff sections on the east coast, as at Langness; on the west coast, north of Peel, and at Contrary Head.

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[1] Hatch: *Rep. Brit. Assoc.* for 1890, p. 814; and Geology of Mallerstang, *Mem. Geol. Surv.*, 1891, *passim*.

[2] *Summary of Progress, Geol. Surv.*, 1903, p. 162.

South-West Scotland. Lamprophyres occur in considerable variety, cutting Silurian rocks in Kirkcudbrightshire. Thus they are strongly developed on the Colvend shore, and at Craigneuk Point, five to six miles south of Dalbeattie. Both micaceous and hornblendic types are found. Mica-lamprophyres (minettes and kersantites) occur at Greenhill, east of Micklewood, 4 miles north of Kirkcudbright; at the Bridge of Dee, $2\frac{1}{2}$ miles south-west of Castle Douglas; and at Glenwharfen Burn, Scarwater, Dumfriesshire. Lamprophyre dykes appear in great abundance in the neighbourhood of the granite complexes, and are probably connected with them in origin. Thus in the Galloway district they are especially abundant in the neighbourhood of the Criffel and Loch Dee granite masses, of which they doubtless represent the basic differentiation products, the complementary acid products being aplites.[1]

North-West Highlands. Lamprophyres allied to minette, but containing microcline instead of orthoclase, occur among the basic dykes in the Lewisian gneiss. The rock of Creag Tombaca, Glen Dhu, $1\frac{1}{2}$ miles east-south-east of Kylesku, may be taken as a type.[2] Hornblendic lamprophyres (vogesites and spessartites) of post-Cambrian age occur abundantly as dark basic sills in the dolomites of the Assynt district,[3] where they are associated with bostonites. (See p. 345.)

[1] Silurian Rocks of Scotland, *Geol. Surv. Mem.*, 1899, p. 627.
[2] North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 98.
[3] North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 452.

Central Highlands. Dykes of lamprophyre are abundant in this district. The Kenmore kersantite and the Carn Dearg vogesite are typical. Minettes and spessartites are rare.[1]

South-West Highlands and Western Isles. Lamprophyres, both of the hornblendic and of the micaceous type (kersantites, vogesites, and camptonites), occur as numerous sills and dykes in the metamorphic rocks of the north and east parts of Cowal, and they are especially developed in Glen Shira and Brannie Burn. The dominant felspar is plagioclase. Phenocrysts of augite, biotite and hornblende occur, according to the special type. The augite is a colourless variety (in thin section). The hornblende occurs frequently in long brown prisms, or in brownish-green hypidiomorphic crystals.[2]

The rock of Glen Catacol, Isle of Arran, described as a syenite,[3] is more correctly a vogesite; for it occurs as a dyke, and consists of idiomorphic brown hornblende in an aggregate of orthoclase and oligoclase.

Ireland. Mica-lamprophyre dykes, intrusive in Silurian rocks, occur in County Louth at 1 mile north-west of Devlin's Bridge, at Starinagh, and at Oriel Demesne. Similar dykes are found at Clogher Head. Both hornblendic and micaceous lamprophyres appear to be of widespread occurrence in the north of Ireland. They occur as thin dykes

[1] Geology of Blair Atholl etc., *Geol. Surv. Mem.*, 1905, p. 119.

[2] Geology of Cowal, *Geol. Surv. Mem.*, 1897, p. 106; and Geology of Mid-Argyll, *ibid.*, 1905, p. 108.

[3] Geology of Arran, *Mem. Geol. Surv.*, 1903, p. 109.

in Ordovician rocks on the coast of County Down. Kersantites occur 3 miles north-west of Downpatrick, and at Ballywater; while a camptonite has been recorded at Dillon, south-east of Downpatrick.[1] A dyke on the shore of South Bay, 3 miles east of Portaferry, contains a blue soda-amphibole (riebeckite or arfvedsonite.)[2] A vogesite with acicular phenocrysts of hornblende in a groundmass of orthoclase, hornblende and interstitial quartz, has been recorded at Clondermot, in the Raphoe area of County Donegal[3]; a camptonite with long needles of brown idiomorphic hornblende, at Lettery in Galway; and a camptonite with both hornblende and biotite, at Rue Bane Point in Antrim.[4] Professor Reynolds has described the occurrence of a hornblende-lamprophyre, with idiomorphic green hornblende, in small intrusions near Tourmakeady, County Mayo.[5]

Channel Islands. Dykes of kersantite occur in Guernsey (*e.g.*, at Moulin Huet and Bec du Nez), and in Jersey (*e.g.*, at St. Helier).

DISTRIBUTION OF MONCHIQUITES.

An interesting series of monchiquites, in association with camptonites and bostonites, has been described by Flett[6] in the Orkneys. One of the chief types

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[1] Watts: Guide, etc., p. 75.

[2] Seymour: *Summary of Progress, Geol. Surv.*, 1899, p. 181.

[3] Watts: Guide, etc., p. 73.

[4] Watts: Guide, etc., p. 77.

[5] Reynolds: *Brit. Assoc. Rep.*, 1908.

[6] Flett: *Trans. Royal Soc. Edin.*, vol. xxix., 1900, pp. 887-896.

is a biotite-monchiquite with abundant phenocrysts of olivine and large plates of biotite. Augite occurs in small crystals of the second generation. The groundmass is decomposed to calcite and fibrous zeolites, so that it is impossible to determine whether it represents an originally glassy residuum, or a final crystallization of nepheline. Another type in the Orkneys is melilite-monchiquite, in which the groundmass consists wholly or in part of melilite in plates of irregular shape. Thin dykes of monchiquite occur also in the Upper Old Red Sandstone of Dunnet Head in Caithness.[1] The rock described as a limburgite[2] from Whitelaw Hill (Chester's Quarry), in Haddingtonshire, appears on further investigation to be probably intrusive in Upper Old Red Sandstone,[3] in which case it is related to the monchiquites. The occurrence of monchiquite has also been recorded among the Tertiary dykes of Argyllshire. Thus on the west side of Camas an Fhais, half a mile north-east of Rudha Fionn Aird, there is a monchiquite containing phenocrysts of anorthoclase.[4]

DISTRIBUTION OF PICRITES.

England. The following are the localities recorded for picrite: Clicker Tor, and Molenicks, in Cornwall; Shelve Pool and Cwmmawr, north-west of Hyssington,

[1] *Summary of Progress, Geol. Surv.*, 1905, p. 115.

[2] Hatch: *Trans. Royal Soc. Edin.*, 1892, pp. 116-117.

[3] *Summary of Progress, Geol. Surv.*, 1904, p. 97.

[4] Flett: *Summary of Progress, Geol. Surv.*, 1907, p. 56.

[5] Ussher: Geology of Plymouth, *Mem. Geol. Surv.*, 1907, p. 101.

in Shropshire; and Little Knott and Great Cockup, near Bassenthwaite, in the Lake District. The latter occurrence is a hornblende-picrite.

North Wales. A beautiful type of hornblende-picrite occurs at Mynydd Penarfynydd in the Lleyn peninsula in Caernarvonshire, where it is intrusive in rocks of Arenig age. It consists of brown hornblende, olivine and felspar, together with a pale augite, brown mica, magnetite and secondary products. The shining cleavage-surfaces of the hornblende are interrupted by dull spots of serpentinized olivine, and thus produce a characteristic lustre-mottling.[1] Another Caernarvonshire locality is Pen-y-rhiwiau, near Clynog-fawr. Similar rocks occur in Anglesey; viz., north-east of the town of Llanerchymedd, Pengorphwysfa, near Amlwch, and at Ty-Croes. The Llanerchymedd rock is black and coarse-grained, with large crystals of hornblende, showing lustre-mottling. According to Harker, it forms laccolithic intrusions in Arenig rocks. The Pengorphwysfa occurrence is a large, irregularly-shaped mass on the western slope of Llaneilian Mountain.

Midland Valley of Scotland. Picrites of well-marked character occur among the Carboniferous rocks of the basin of the Forth, as at Blackburn, near Bathgate; Barnton Railway Station;[2] and on the island of Inchcolm. The Inchcolm rock is a singularly beautiful type: besides olivine, augite and felspar, it contains brown hornblende, biotite, iron-ore, apatite,

[1] Harker: *Quart. Journ. Geol. Soc.*, vol. xliv. (1888), p. 454.
[2] Monckton: *Quart. Journ. Geol. Soc.*, vol. l. (1894), 39.

and a vivid bluish-green serpentinous mineral derived from the alteration of the olivine. A fibrous green hornblende (pilite) is also developed to some extent.[1] A very similar rock has recently been discovered at Lethan Hill, Waterside, Ayrshire; another occurs at Turnberry Castle, 6 miles north of Girvan, on the Ayrshire coast.

Western Isles and Highlands of Scotland. Judd[2] has recorded the association of picrites with the Tertiary gabbros and dolerites of Rum, the West of Skye, and the Shiant Isles. Hornblende-picrites also occur in many of the igneous complexes of the Central Highlands and South-West Highlands. Typical picrites occur as dykes in the Lewisian gneiss, *e.g.*, on the south side and near the outlet of Loch Assynt, about 2 miles on the road from Lochinver to Inchnadamff. These dykes show passages to hornblende-schist, and some are much serpentinized.

DISTRIBUTION OF PERKNITES.

Various members of this family are represented as bands in the Lewisian gneiss of Sutherland (*e.g.*, at Scourie), and in other areas. The occurrence in Ross-shire[3] of small lenticular sills of hornblendite containing garnet, has been noted by the Geological Survey. An eclogite composed of omphacite and garnet with accessory rutile, has been recorded

[1] A. Geikie: *Trans. Roy. Soc. Edin.*, vol. xxix. (1880), p. 504.
[2] Judd: *Quart. Journ. Geol. Soc.*, vol. xli. (1885), p. 393.
[3] *Summary of Progress, Geol. Surv.*, 1901, p. 109.

at Beinn a Chapuill in the Glenelg district.[1] A scapolite-bearing perknite has been described by Flett[2] from Badcall, in Sutherland. It consists chiefly of dark green or brownish-green hornblende, pale green augite and scapolite. Hypersthene also occurs, but less abundantly.

DISTRIBUTION OF PERIDOTITES.

Peridotites occur as the most basic products of differentiation of deep-seated magmas, in association with picrites, pyroxenites, hornblendites, gabbros, etc. Thus they are found among the Tertiary plutonic rocks of Skye and of Rum;[3] and appear as dykes in the fundamental complex of the North-West Highlands,[4] and of Connemara in Ireland. Wehrlite and other peridotites occur as basic differentiations in the plutonic complex of Garabal Hill, near the head of Loch Lomond, in the Southern Highlands. Scyelite or biotite-hornblende-peridotite has been described by Judd[5] from the western border of Caithness (Loch Scye), and the same type has been recorded in Ross-shire at Carn Cas nan Gabhar.[6]

A peridotite of remarkable freshness (cortlandtite) consisting of hypersthene, amphibole, and olivine

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[1] *Summary of Progress, Geol. Surv.*, 1899, p. 176.

[2] *Summary of Progress, Geol. Surv.*, 1906, p. 124.

[3] Harker: The Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1906, p. 374, *and* The Small Isles, *ibid.*, 1908.

[4] Geology of the North-West Highlands, *Mem. Geol. Surv.*, 1907, p. 44.

[5] Judd: *Quart. Journ. Geol. Soc.*, vol. xli., 1885, p. 393.

[6] Flett: *Summary of Progress, Geol. Surv.*, 1901, p. 109.

with magnetite, has been recorded by Sollas at Derreennagusfoor, four miles south-east of Maum Hotel, in County Galway.[1] Hornblende-peridotites associated with amphibolites, occur in small intrusions and dykes in Ordovician strata at Glendalough and Greystones, in the eastern part of County Wicklow.[2]

DISTRIBUTION OF SERPENTINES.

Serpentine occurs in many localities in Cornwall (Lizard district), Anglesey, Ayrshire (Lendalfoot, Ballantrae, and Balhamie Hill near Colmonell), Aberdeenshire, and Banffshire (Portsoy). In Forfarshire and Perthshire there are dykes of serpentine; and as a derivative from an olivine-enstatite rock it forms the Coyles, conspicuous hills lying some 4 miles west of Ballater, in the Central Highlands. As an alteration product of peridotites it also forms a part of the igneous complex of Garabal Hill, near the head of Loch Lomond, in the Southern Highlands.

In the west of Ireland serpentines occupy a considerable area in Northern Galway and Sligo. The famous green "ophicalcite" of Connemara is chiefly from quarries near Clifden and at Lissoughter. Many of these rocks are probably derived from the alteration of olivine-bronzite rocks like saxonite, as they contain numerous crystals of bastite.

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[1] *Rep. Geol. Surv.*, 1895, p. 38.

[2] J. A. Thomson: *Quart. Journ. Geol. Soc.*, vol. lxiv., 1908, p. 475.

CHAPTER III.

DISTRIBUTION OF THE VOLCANIC ROCKS.

DISTRIBUTION OF RHYOLITES.

Midland Counties, England. Rhyolitic lavas, which appear to be of pre-Cambrian age, occur in Shropshire, at the Wrekin near Wellington, at Caer-Caradoc near Church Stretton, near Wrockwardine, and at Pontesford Hill on the Longmynd.[1] The Lea rock at Overlay Hill, near Wellington, consists of a beautiful red spherulitic rhyolite, showing a well-marked flow-structure; and the Wrockwardine and Pontesford Hill rocks contain spherulitic nodules, similar to the well-known ones of Boulay Bay in Jersey.[2]

Lake District. Rhyolites form a part of the Borrowdale volcanic series. They are felsitic rocks, presenting strong flow structures, and occasionally containing garnets (as at Illgill Head). They occur in Langdale (Dungeon Ghyll), on Crinkle Crags

[1] Professor Lapworth informs me that there can be no doubt of the pre-Cambrian age of these lavas, since there are pebbles of the rhyolites in the basal conglomerate of the Cambrian quartzite at Caer-Caradoc.

[2] Parkinson: *Quart. Journ. Geol. Soc.*, vol. lvii., 1901, p. 220; and W. S. Boulton: *Quart. Journ. Geol. Soc.*, vol. lx., 1904, p. 450.

(Gunson Knott) and Great Gable (Sty Head), near Stickle Tarn, in the Copper Mine Valley, near Grizedale Tarn, in Long Sleddale, and near Great Yarlside. A nodular variety occurs between Shap Wells and Stockdale.

North Wales. Very acid rhyolites (composed of porphyritic crystals of quartz and felspar in a felsitic base) form the Llyn Padarn ridge, and crop out near Bangor. They are held to be of pre-Cambrian age. The great majority of the rhyolitic lavas of Caernarvonshire are, however, of Ordovician (Bala) age. They are grouped by Harker [1] in four series, namely:—

1. Dwygyfylchi and Y Drosgl series.
2. Pen-yr-Oleu-wen and Carnedd Llewellyn series.
3. Y Glyder-fach, Capel Curig and Conwy Mountain series.
4. Snowdonian series.

The Snowdonian lavas can be studied on Snowdon, Moel Hebog, and in the Gwynant and Glaslyn valleys. They form the plateau of Llwyd-mawr, and occur in numerous outliers; *e.g.*, west of Dolwyddelen, Moel Siabod, Llyn Lledr, and near Bettws-y-Coed; also west and east of Pwllheli, and near Llanbedrog, in the Lleyn peninsula.

These rocks consist of a compact felsitic base containing scattered crystals of quartz and felspar. When fresh they are dark-coloured; but when weathered they are lighter in colour and possess a

[1] The Bala Volcanic Series of Caernarvonshire, *Sedgwick Prize Essay for 1888*, 1889, p. 9.

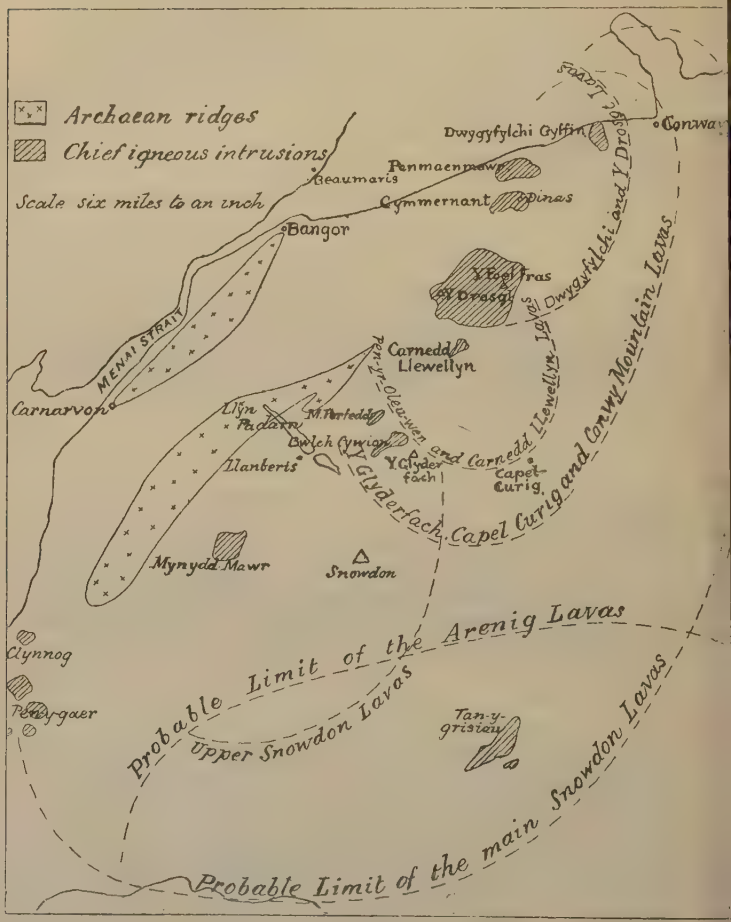

FIG. 125.

Sketch-map of North Wales, showing the distribution of the intrusive rocks and lavas. (*After A. Harker.*)

laminated character, due to original flow-structure (Clogwyn-dur-Arddu). Streaks and lenticles of quartz sometimes follow the lines of flow. Ferromagnesian minerals are subordinately developed, and are invariably represented by a pale chlorite. The rocks are frequently nodular, and often present spherulitic and perlitic structures. Some of the best localities for the nodular variety are: Conwy Falls, Digoed and other places near Bettws-y-Coed; near Capel Curig, Glyder-fawr, Esgair-felen, at the head of Llanberis Pass; and in the Lleyn peninsula at Pwllheli and Pen-y-chain.

Rhyolites are represented in the Coomb volcanic series (Arenig) at Llangynog, 6 miles south-west of Caermarthen. They are pale grey to blue, and consist of phenocrysts of orthoclase and plagioclase set in a silicified groundmass showing flow-structure. The acid lavas were extruded between two eruptions of andesite.[1] Rhyolites of Arenig age are also developed at Mynydd y Gader, Dolgelly.

South Wales. In the Fishguard district rhyolitic lavas of Llandeilo and Bala age occur. They are characterised by a high percentage of silica, combined with high alkalies, both potash and soda.[2] Speaking generally, they consist of phenocrysts of quartz and orthoclase in a microfelsitic groundmass; but the structure of the latter is variable. Similar lavas (the Llanrian series) occur at Abereiddy Bay.[3] Rhyolites

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[1] Cantrill and Thomas: *Q. J. G. S.*, vol. lxii. (1906), p. 223.

[2] Cowper Reed: *Q. J. G. S.*, vol. li. (1895), p. 177.

[3] Elsden: *Q. J. G. S.*, vol. lxi. (1905), p. 580.

also occur in Ramsey and Skomer Islands, off the coast of Pembrokeshire. The Skomer Island rocks are nodular.

Scotland. Rhyolitic lavas of Lower Old Red Sandstone age occur in the Glencoe volcanic series of the Western Highlands.[1] (See Fig. 130, p. 371.) They are only sparsely developed in the Tertiary volcanic area of the Western Isles: Harker[2] describes a small group, in association with trachytes, on the northern border of the Cuillin Hills, in Skye. They resemble the rhyolites of Iceland.

Ireland. A great series of red rhyolitic flows of Lower Llandeilo age occurs in the Tourmakeady district of County Mayo.[3] Nodular and banded rhyolites are associated with Wenlock and Llandovery beds at Clogher Head, in County Kerry.[4] A spherulitic rhyolite occurs at Lough Guitane among the Dingle beds (Old Red Sandstone) of Killarney.[5] Fine rhyolites occur in the Tertiary volcanic area of County Antrim at Templepatrick, Tardree and Ballymena. These were erupted in Eocene times, between the outpouring of the lower and the upper basalts. They are light-coloured rocks, containing phenocrysts of quartz and sanidine in a microlitic groundmass. In structure they vary from compact and lithoidal to crystalline and porphyritic. The Templepatrick rock shows flow-structure, and a glassy

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[1] *Summary of Progress, Geol. Surv.*, 1905, pp. 95 and 98.

[2] The Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 61.

[3] Reynolds and Gardiner: *Rep. Brit. Assoc.*, 1908.

[4] Reynolds and Gardiner: *Q. J. G. S.*, 1902, p. 226.

[5] Watts: Guide, etc., p. 92.

type (obsidian) occurs at Sandy Braes. In this rock a perlitic structure is developed, which not only affects the glass, but extends to the enclosed quartz crystals.[1]

Jersey. A well-known spherulitic rhyolite occurs in Northern Jersey at Boulay Bay.

DISTRIBUTION OF PHONOLITES.

England. The phonolite of the Wolf Rock, off the coast of Cornwall, is the only representative of the nepheline rocks in England. It consists of sanidine, nepheline, nosean, and ægirine.

Scotland. A dark-brown to grey phonolite occurs at Traprain Law in Haddingtonshire. This is a vent from which doubtless lavas were emitted in Lower Carboniferous times; but these have been completely removed by denudation. The rock consists of sparsely-developed nepheline, a bright-green soda-augite (ægirine or ægirine-augite), and sanidine felspar, the latter in small, lath-shaped crystals with parallel arrangement producing a marked flow-structure. Phenocrysts are rare.[2]

Similar rocks have been described from Skelfield Pen, 8 miles south of Hawick, and Pikethaw Hill, Teviot Head, 13½ miles south of Hawick.[3]

DISTRIBUTION OF TRACHYTES.

Devonshire. Trachytes are represented in the Permian volcanic series near Exeter: thus biotite-

[1] Watts: *Quart. Journ. Geol. Soc.*, vol. l. (1894), p. 367.

[2] Hatch: *Trans. Royal Soc. Edin.*, vol. xxxvii. (1892), pp. 115 and 116.

[3] H. J. Seymour: *Summary of Progress, Geol. Surv.*, 1900, p. 164.

trachyte occurs at Kellerton Park, near Exeter; at Knowle, Spencecomb, near Crediton; and at Copplestone, near Knowle Hill. The rock quarried at Pocombe appears to be a representative of the ciminite sub-family (see p. 260), since it contains both plagioclase and orthoclase in lath-shaped microlites, together with numerous red pseudomorphs after olivine, and augite in sparsely-scattered grains, often altered to carbonates.[1]

Scotland. In the Garlton Hills of Haddingtonshire the uppermost division of the Carboniferous lavas consists of trachytes: among them is a well-developed porphyritic type composed of large phenocrysts of sanidine felspar (with which oligoclase is occasionally associated), imbedded in a groundmass of lath-shaped felspars. The phenocrysts are packed in glomero-porphyritic fashion. Such rocks are well seen in the Peppercraig quarries near Haddington, at Dirleton Craig, at Kae Heughs, under the Hopetoun Monument, in the Phantassie and Bangley quarries, and at Skid Hill. A non-porphyritic type of the trachyte occurs at Score Hill, Lock Pit Hill, Craigie Hill, and Pencraig.[2] These are pale-coloured rocks of buff, pink, and mauve tints. They consist of a mass of closely-interlaced felspars of tabular habit, and in consequence have a somewhat glistening appearance. A marked microfluidal structure is occasionally evidenced by the parallel arrangement of the microlites. The vents from which these trachytes

[1] Teall: *Summary of Progress, Geol. Surv.*, 1899, p. 171.
[2] Hatch: *Trans. Roy. Soc. Edin.*, 1892, p. 121.

flowed are represented by the trachyte domes of North Berwick Law and the Bass Rock.

Trachytes also occur in association with the Old Red Sandstone andesitic lavas of the Pentland and the Braid Hills (*e.g.*, at Morton Hall in the Braid Hills, and at Woodhouselee, Pentland Hills). A trachyte occurs at the Eildon Hills, near Melrose. It consists essentially of short prisms of alkali-felspar and soda-bearing ferro-magnesian minerals. At one place (Mid-Eildon Hill), the trachyte contains riebeckite. Soda-trachytes of Upper Bala age occur at Hamilton

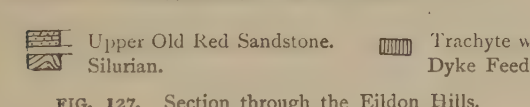

FIG. 127. Section through the Eildon Hills.
(*After B. N. Peach.*)

Hill, north-east of Peebles; and at Wrae Quarry and Glencotho Quarry, Holmswater, near Broughton. They consist mainly of alkali-felspar (anorthoclase) in small phenocrysts set in a microlitic groundmass.[1]

A few trachytic flows have been recorded among the Tertiary volcanic rocks of Skye, as at Fionn-Choire, on the northern side of the Cuillin Hills.[2]

Ireland. Trachyte occurs in volcanic vents near the edge of the Limerick volcanic basin.[3]

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[1] Teall: Silurian Rocks, *Geol. Surv. Mem.*, vol. i., 1899, p. 88.

[2] Harker: Tertiary Igneous Rocks of Skye, *Mem. Geol. Surv.*, 1904, p. 88.

[3] Watts: Guide, etc., p. 93.

DISTRIBUTION OF DACITES.

Dacites have been recorded by Hill and Bonney in Charnwood Forest at Peldar Tor, High Sharpley and Bardon (Maplewell Series). These lavas are associated with tuffs. They are certainly of pre-Carboniferous, and probably of Archæan age. Flett has described dacites of Old Red Sandstone age at Leuchars and Wormit Bay, on the south side of the Firth of Tay, in Eastern Fife.[1]

DISTRIBUTION OF ANDESITES.

Devon and Cornwall. The Permian volcanic series of Exeter contains, besides the trachytes, some andesites, as at Ide and Kellerton Park.

Bristol District. In the neighbourhood of Tortworth (*e.g.*, at Charfield Green, Damery Bridge, Avening Green, Horsley Quarry, and Daniel's Wood) pyroxene-andesites associated with tuffs, occur on two horizons: the one overlaid by beds of Upper Llandovery age, and the other by beds of Lower Wenlock age. They consist of phenocrysts of labradorite and andesine in a groundmass of felspar laths and needles. The pyroxene is altered to bastite, or serpentine.[2] In the Eastern Mendips there is, north of Shepton Mallet, an interesting inlier of Silurian rocks, with which andesite lavas are associated, as at Moons Hill and Beacon Hill. These rocks contain conspicuous phenocrysts of plagioclase and bastite pseudomorphs after enstatite.[3]

[1] The Geology of East Fife, *Mem. Geol. Surv.* (1902), p. 387. *See also* Judd: *Quart. Journ. Geol. Soc.*, vol. xlii., 1886, p. 425.

[2] Lloyd Morgan and S. H. Reynolds: *Quart. Journ. Geol. Soc.*, vol. lvii., 1901, p. 267.

[3] Reynolds: *Q. J. G. S.*, 1907, p. 218.

Lake District. The vast accumulation of volcanic material known as the Borrowdale Volcanic Series,

FIG. 128.

Sketch-map of the Lake District.

is mainly made up of andesitic lavas and tuffs. As a rule the lavas are compact, dark-coloured rocks, com-

posed of numerous slender laths of felspar, with occasional large phenocrysts of plagioclase, and a glassy brownish base. The augitic constituent is generally replaced by chlorite. Rocks of this character are well developed to the south of Keswick and in Borrowdale (*e.g.*, Brown Knotts, Bleaberry Fell, Iron Crag, High Rigg); and in Langdale, Westmorland (Lingmoor, Side Pike, Chapel Stile). A more porphyritic type occurs on Great Gable. Andesitic lavas belonging to the Borrowdale Series also occur at Bootle in Cumberland, and at Shap Fell, Westmorland.

The Eycott lavas, which occur at Eycott Hill, one mile from Troutbeck station, near Keswick, and in the Cross Fell range, constitute a more basic type, probably more correctly to be classified with the basalts (see p. 374). Some of the members of this series are very porphyritic, containing fine large crystals of a striped plagioclase felspar (bytownite to anorthite). There are crystals of idiomorphic hypersthene altered to bastite.

Northumberland. A series of andesitic lava-flows occurs in the Carboniferous Limestone Series of the river Tweed, near Carham Hall.

Cheviot District. Andesites (augite- and enstatite-andesite) of Old Red Sandstone age occur in great abundance in the Cheviot Hills (Northumberland and Roxburghshire). In texture they show considerable variety, being fine-grained or porphyritic, felsitic or glassy, compact or vesicular. A glassy type with streaky flow-structure occurs at Yetholm. A glassy and perlitic type occurs at Buckham's Wall Burn (Northumberland), and at the

Curr, 4½ miles east of Morebattle (Roxburghshire). Occasionally the rocks assume a more trachytic character, with development of sanidine instead of a striped felspar (*e.g.*, near Jedburgh).

Wales. The Ordovician rocks of Merionethshire and Caernarvonshire consist largely of andesitic lavas and their tuffs, building up a considerable portion of the mountain ranges of Cader Idris, the Arans, Arenig Fawr, Arenig Fach, Manod and Moelwyn. These hills form a semi-circle round the Cambrian rocks of the Harlech dome, extending from Barmouth through Dolgelly to Ffestiniog. In the Lleyn Peninsula Harker has described augite-andesites from Penmaen Castle, 1 mile west of Pwllheli, and Y Foel Fawr, 1½ miles west of Llanbedrog.

Ordovician andesites occur in the hills of the Shelve district, near the boundary between Shropshire and Montgomeryshire. Here lavas of Arenig age form the Stapeley Hills, from Llanfawr to Symonds Castle, attaining their greatest thickness and extent on Todleth. These lavas contain phenocrysts of plagioclase, augite, and hypersthene in a fine microlitic groundmass. Often the phenocrysts are aggregated in glomero-porphyritic fashion.[1] In the same area, thick sheets of ash of similar composition are intercalated in the Upper Arenig, and in the Bala rocks. Precisely similar hypersthene-andesites occur amongst the Bala ashes of the Breidden Hills (*e.g.*, at Moel-y-Golfa, 6 miles north-east of Welshpool), which are really an outlying portion of the Corndon area. Vesicular

[1] Watts: *Proc. Geol. Assoc.*, vol. xiii., p. 297.

andesites and their tuffs also occur near Builth, in the range of the Carneddau (Herefordshire and Radnorshire), where there is an outlier of Ordovician rocks.[1]

Andesites and associated tuffs, which are probably of Arenig age, also occur at Coomb, Llangynog, 6 miles south-west of Caermarthen. These are compact vesicular rocks, which, under the microscope, are seen to consist of lath-shaped phenocrysts of oligoclase or andesine, set in a groundmass of felspar microlites. The ferro-magnesian mineral, which was mainly augite and more rarely hornblende, is completely decomposed to chlorite and quartz.[2]

Midland Valley of Scotland. Augite- and enstatite-andesites of Old Red Sandstone age are well developed in the Midland Valley, building the hill-ranges of the Pentlands, the Braid Hills, and the Ochils. The rocks are compact, occasionally amygdaloidal, and vary in colour from black, through various shades of purple and brown, to dun and cream colours. Under the microscope they are seen to consist of phenocrysts of plagioclase felspar, together with more or less altered enstatite and augite, imbedded in a groundmass of lath-shaped felspars and glassy matter. Strongly amygdaloidal andesites occur in Ayrshire (Turnberry Point and Culzean). Andesites of Lower Carboniferous age also occur in the Midland Valley, among the lavas forming the Campsie Hills, the Kilpatrick Hills, and the Renfrewshire Hills, and in the Mull of Kintyre and the Island of Bute. (See Fig. 129.)

[1] H. Woods: *Quart. Journ. Geol. Soc.*, vol. l., 1894, p. 566.

[2] T. C. Cantrill and H. H. Thomas: *Quart. Journ. Geol. Soc.*, vol. lxii. (1906), p. 223.

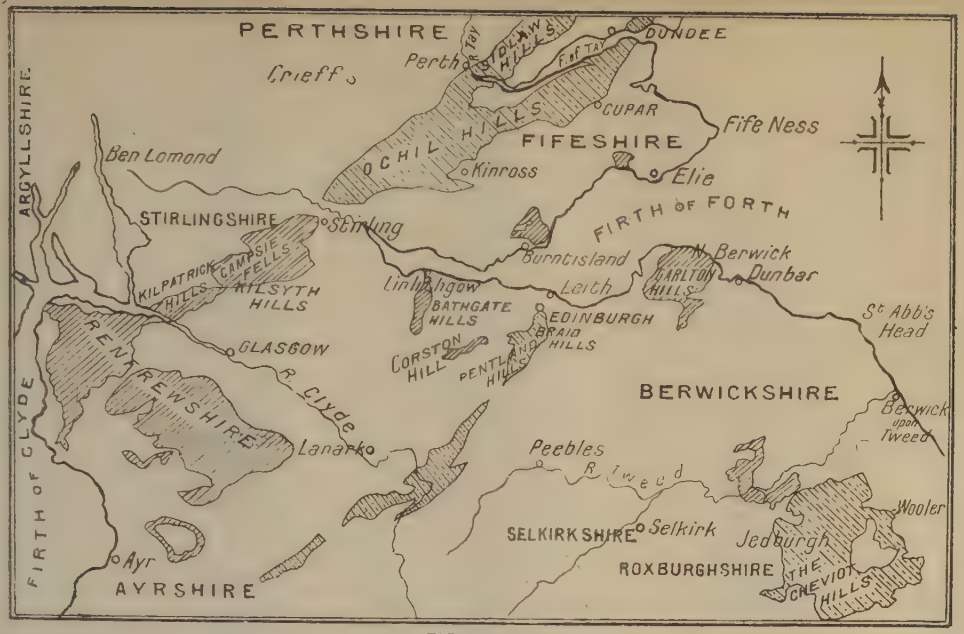

FIG. 129.

Map of Volcanic Rocks in the Midland Valley of Scotland.

Lavas of Carboniferous Age.

Lavas of Old Red Sandstone Age.

South-West Highlands. A thick series of andesitic lavas associated with fragmental volcanic rocks, and sandstone and conglomerate of Old Red Sandstone age, occur in Lorne between Loch Awe and Loch Etive, and in the neighbourhood of Glencoe. These andesites are dark-coloured, and compact to vesicular. Hornblende-andesites are largely developed amongst them, as at Buchaille Etive Mòr, but augite-, hypersthene- and biotite-andesites also occur.[1] (See Fig. 130.)

Ireland. Andesites of Carboniferous age occur near Limerick, in the so-called Limerick Basin. They are associated with tuffs, and are evidently lava-flows. They consist of large phenocrysts of zoned plagioclase, embedded in a groundmass of felspar microlites, together with granular enstatite and magnetite. Andesites of Upper or Middle Bala age, including varieties with augite and hypersthene, occur on Lambay Island, off the east coast of County Dublin. They are associated with pyroclastic rocks, and mark an extensive outburst of vulcanicity in Bala times, the focus of which could not have been far distant.[2] Similar lavas, and of the same age, occur on the mainland in the Portraine inlier of pre-Devonian rocks,[3] and in the Kildare inlier, 35 miles further to the south-west.[4]

[1] *Rep. Geol. Surv.* for 1896, p. 53 ; also *Summary of Progress, Geol. Surv.*, 1897, p. 84 ; and 1905, p. 99. Also *Q. J. G. S.*, 1909, p. 615.

[2] Gardiner and Reynolds : *Quart. Journ. Geol. Soc.*, vol. liv. (1898), p. 147.

[3] Gardiner and Reynolds : *Quart. Journ. Geol. Soc.*, vol. liii. (1897), p. 520.

[4] Gardiner and Reynolds : *Quart. Journ. Geol. Soc.*, vol. lii. (1896), p. 587.

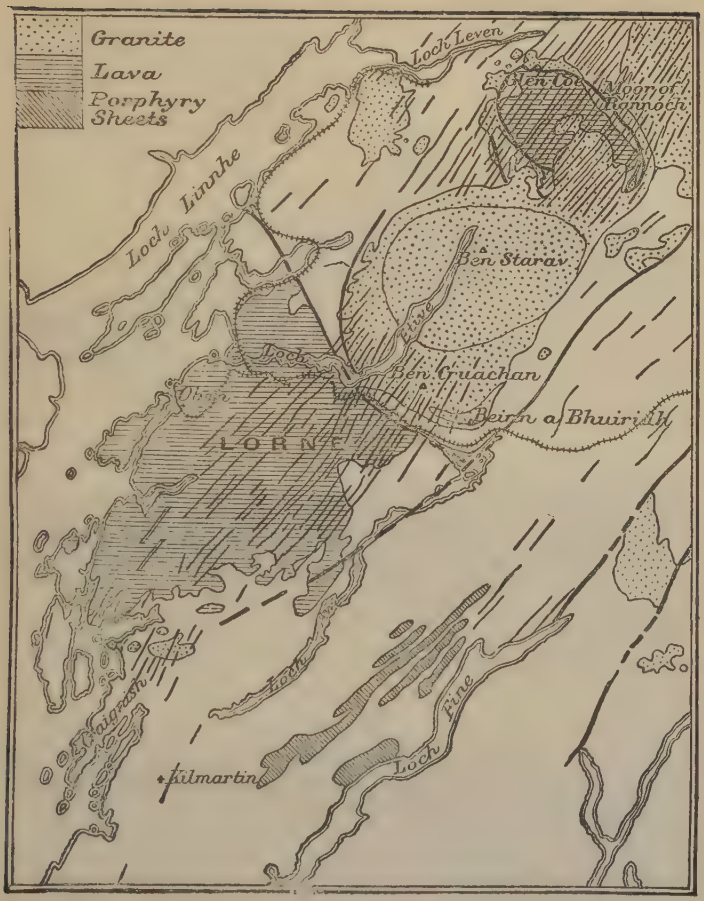

FIG. 130.

Sketch-map of the volcanic district of Northern Argyllshire (Glencoe), showing the distribution of the lavas of Old Red Sandstone age and of the dykes (chiefly porphyrite: *cf.* p. 325), in relation to the Etive granite complex. The Highland schists are left white. Faults are shown by heavy black lines. (*After Clough, Maufe, and Bailey: The Cauldron-subsidence of Glencoe.*)

DISTRIBUTION OF BASALTS.

Devon and Cornwall. Vesicular basic lavas associated with breccias and tuffs, occur interbedded with the Devonian rocks of these counties. Thus in *Cornwall,* well-defined lavas occur at Endellion, St. Minver, St. Clether and near Padstow. In *Devonshire* the Middle Devonian[1] volcanic series of Ashprington and Totnes, described by Messrs. Champernowne and Ussher, consists of basaltic lavas much chloritized and impregnated with carbonates. They are often weathered to a rusty-red colour, and, together with the associated tuffs, have been frequently sheared into schistose rocks (*Schalstein*). In the lavas the flattened chloritic amygdales can sometimes still be recognized. A typical specimen from Sharpham Barton consists of isolated phenocrysts of plagioclase set in an altered groundmass of augite, felspar, iron-ore and chlorite.[2] Scoriaceous basic lavas, together with tuffs and breccias, occur at Brent Tor, near Tavistock. They were probably erupted from a volcanic vent, of which Brent Tor itself represents the denuded stump.[3]

Olivine-basalts of Permian age are found in association with trachytic rocks in the neighbourhood of Ide and Dunchideock, near Exeter. They are much

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[1] According to Ussher the eruption of basic lavas appears to have commenced in the Lower Devonian and continued to as late as the base of the Upper Devonian. *Mem. Geol. Surv., Sheet 350,* 1903, p. 9.

[2] Hatch : *Mem. Geol. Surv. England, Sheet 350,* 1903, p. 79.

[3] Rutley : Brent Tor, *Mem. Geol. Surv.* (1878).

altered, the olivine being replaced by a red decomposition product. A characteristic feature is the presence of corroded grains of quartz.[1]

Derbyshire. Contemporaneous flows of basaltic lava occur in the Carboniferous Limestone of this county. These rocks, locally known as "toadstone,"[2] are strongly amygdaloidal, and are often much decomposed. They are olivine-basalts, composed of phenocrysts of plagioclase, olivine and augite, in a groundmass of lath-shaped felspars, with interspersed granules of augite and magnetite, or some glassy base. A variation of type is produced by the subordination of one or other of the porphyritic constituents. The olivine is usually altered to serpentine and oxide of iron, and the augite is seldom quite fresh. The lavas are accompanied by tuffs, and some of the volcanic vents have been located by Dr. Arnold-Bemrose.[3] This observer distinguishes between three main areas of volcanic activity: namely, that of Miller's Dale, that of Matlock, and that of Tissington. In the Miller's Dale and Matlock areas the igneous intrusions are confined to the Mountain Limestone; and two main flows may be traced for several miles. But in the Tissington area they occur in the Yoredale Shales; and the lava flows are of small extent. With regard to the difference between the two first-named areas, in that of Miller's Dale the upper lava is the thicker (about

[1] *Summary of Progress, Geol. Surv.*, 1899, p. 171; see also Hobson: *Quart. Journ. Geol. Soc.*, vol. xlviii., 1892, p. 496.

[2] Probably so-called from its speckled appearance.

[3] *Quart. Journ. Geol. Soc.*, vol. lxiii. (1907), p. 241.

100 feet), and extends over a greater distance than the lower, while in that of Matlock the reverse holds good. Again, in the Miller's Dale area the lavas are separated by almost 150 feet of limestone, and in the Matlock area, by only 80 to 100 feet. The upper lava of Miller's Dale is on a lower horizon than the lower lava of Matlock, and the limestones above it contain at least two bands of interbedded tuff. The more important vents in the Miller's Dale area are at Speedwell, Castleton; Monksdale; and Calton Hill. In the Matlock area, vents occur at Cracknowl, Bakewell; Grangemill; Ember-Lane and Hopton. In the Tissington area, lava-flows occur south of Kniveton; and west of Shaw's Farm, north of Tissington. With these exceptions, the evidence of volcanic activity of this area is confined to vents of agglomerate in the Mountain Limestone, and in the Yoredale Rocks, and to bedded tuff in the latter. The vents occur at Kniveton Cottage and at Woodeaves; while a bed of tuff 140 feet thick, consisting of lapilli of a pumiceous rock, was opened in cuttings of the Ashbourne and Burton railway, between Tissington and Crakelow.

Small patches of Carboniferous basalt, associated with tuffs and breccias, occur in the Mendips, and near Weston-super-Mare, in Somerset. The best sections are at Middle Hope, and at Spring Cove, immediately to the west of the farm of Weston, where a highly amygdaloidal olivine-basalt, showing "pillow" structure, is interbedded with Carboniferous Limestone, containing volcanic dust and vesicular lapilli. Other exposures are at Goblin Combe, north of Wrington.

The Spring Cove lava is much decomposed, but contains pseudomorphs after olivine and augite in a microlitic groundmass.[1]

Shropshire. Basaltic lavas occur as a middle group in the pre-Cambrian volcanic series of Pontesford Hill on the north-west flank of the Longmynd. They are associated with felspathic and glassy types. The silica percentage of a specimen of these lavas is 50·67. They consist of a felted aggregate of felspar laths (oligoclase), together with a good deal of augite (malacolite), occasionally enclosing microlites of felspar.[2] Phenocrysts of felspar also occur, but are rare.

North of England. Basaltic lavas of Carboniferous age occur in the Cheviots; for instance, on the east side of Hungry Law, Ramshope Burn; and in Cottonshope Burn, Reedwater. Some of the lavas of Eycott Hill, near Keswick, are hypersthene-basalts. (See p. 336.)

Wales. Vesicular flows of basalt containing a little olivine occur in Skomer Island, off the coast of Pembrokeshire. Basic material was also erupted at Rhobell Fawr, 5 to 6 miles north-north-east of Dolgelly; but these rocks consist mainly of pyroclastic material, often containing crystals of hornblende. The lavas are dark-coloured and compact

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[1] Teall: *Summary of Progress, Geol. Surv.*, 1898, p. 104. See also Lloyd Morgan and S. H. Reynolds: *Quart. Journ. Geol. Soc.*, vol. lx., 1904, p. 137; and W. S. Boulton: *ibid.*, p. 158.

[2] W. S. Boulton: *Quart. Jour. Geol. Soc.*, vol. lx., 1904. p. 470.

rocks, composed of felspar and augite and free from olivine. A vesicular type east of Ty-Canol contains hornblende in addition to augite. According to Messrs. Cole and Holland they are of Tremadoc age, and lie on the upturned edges of the Lingula Flags.[1]

Vesicular basaltic lavas of Ordovician age occur in Ramsey Island (Porth Hagog).

Scotland. The basalts of Scotland belong chiefly to two volcanic periods: (1) the Carboniferous, developed in the *Midland Valley;* (2) the Tertiary, developed in the *Western Isles.*

The Carboniferous basalts[2] were erupted during the earliest portion of the period. They present many various types of structure and composition. They mostly contain olivine: some are even very rich in this mineral, approximating then to the composition of limburgites. Among the commoner types are the following:—[3]

(1) *Lion's Haunch Type.* Large phenocrysts of olivine, augite, and felspar in a groundmass of felspar laths, granular augite, magnetite, and occasionally glassy interstitial matter. Examples: Lion's Haunch, Arthur's Seat, and Calton Hill.

(2) *Craiglockhart Type.* Phenocrysts of olivine

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[1] *Geol. Mag.*, 1890, p. 447, and *ibid.*, 1893, p. 337.

[2] It is difficult in the case of these rocks to separate those that were actually erupted at the surface, from those that are found in necks and pipes representing the vents through which flowed the lavas that reached the surface. Some of the types mentioned here occur also as such intrusions.

[3] F. H. Hatch and W. W. Watts: *Rep. Geol. Surv.* for 1896, p. 64, and The Geology of Central and East Fife. *Mem. Geol. Surv.*, 1900, p. 53.

and augite in a groundmass of felspar laths and granular augite. Examples: Craiglockhart Hill, Edinburgh, and in the Kilpatrick Hills, north-east of Glasgow.

(3) *The Dalmeny Type.* Abundant phenocrysts of olivine, less of augite and none of felspar, embedded in a mesh of slender lath-shaped felspars, the interspaces being filled with microlitic augite and minutely granular magnetite. Examples: Dalmeny; in the Bathgate Hills of Linlithgowshire (Hillhouse and Kirton West Quarry); in Fife, between Burntisland and Kirkcaldy, and along the coast from Pettycur to Kinghorn.

(4) *Kippie Law Type.* Phenocrysts of olivine and felspar in a groundmass of lath-shaped felspars, granular olivine and magnetite, and microlitic augite. Examples: Kippie Law in the Garlton Hills of Haddingtonshire; and in the Kilsyth Hills.

(5) *Markle Hill Type.* A macro-porphyritic basalt, consisting of large phenocrysts of labradorite and small sporadic grains of olivine in a groundmass of felspar microlites and magnetite granules. Examples: Garlton Hills (Markle Quarry and Hailes Castle), Arthur's Seat, Edinburgh; in the Kilsyth Hills, and on the Campsie Fells.

(6) *Jedburgh Type.*[1] A micro-porphyritic basalt, with small phenocrysts of olivine and less of felspar in a groundmass of augite and felspar in sub-ophitic intergrowth. Examples: Near Jedburgh, and on the Campsie Fells.

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[1] Compare the Gallaston type described on p. 339.

(7) *Kilsyth Type.*[1] Strongly porphyritic basalt, with large phenocrysts of felspar and smaller ones of olivine; groundmass sub-ophitic—Kilsyth Hills.

These basalts are associated in the Garlton Hills with more basic rocks such as picrite and a limburgite or monchiquite type, as well as with more acid lavas—trachytes, and phonolites.[2]

In the Campsie Fell area, Mr. Bailey[3] of the Geological Survey has recently worked out the following succession for the Carboniferous volcanic rocks north of Kilsyth; the horizon upon which rest the volcanic rocks is lower than in the type section of Ballagan, to the west, or of Fintry, to the north. The Cementstone group is almost unrepresented, and the volcanic beds succeed the Cornstone group of the Upper Old Red Sandstone. The succession also is different. In the Ballagan section it is:

(*d*) *Upper group* with several basalts of the Markle type and mugearites.

(*c*) *Lower group* consisting of basalts of the Jedburgh type.

(*b*) *Cementstone group.*

(*a*) *Cornstone group.*

Whereas, north of Kilsyth, the succession is:

(*d'*) *Upper group* characterized by basalts of the Markle type.

(*c'*) *Lower group* of basalts of the Jedburgh type.

(*b'*) *Still lower group* characterized by several basalts of the Markle type.

(*a'*) *Cornstone group.*

[1] Compare the Gallaston type described on p. 339.

[2] Hatch: *Trans. Roy. Soc. Edin.*, vol. xxxvii., 1892, p. 115.

[3] *Summary of Progress, Geol. Surv.*, 1907, p. 93.

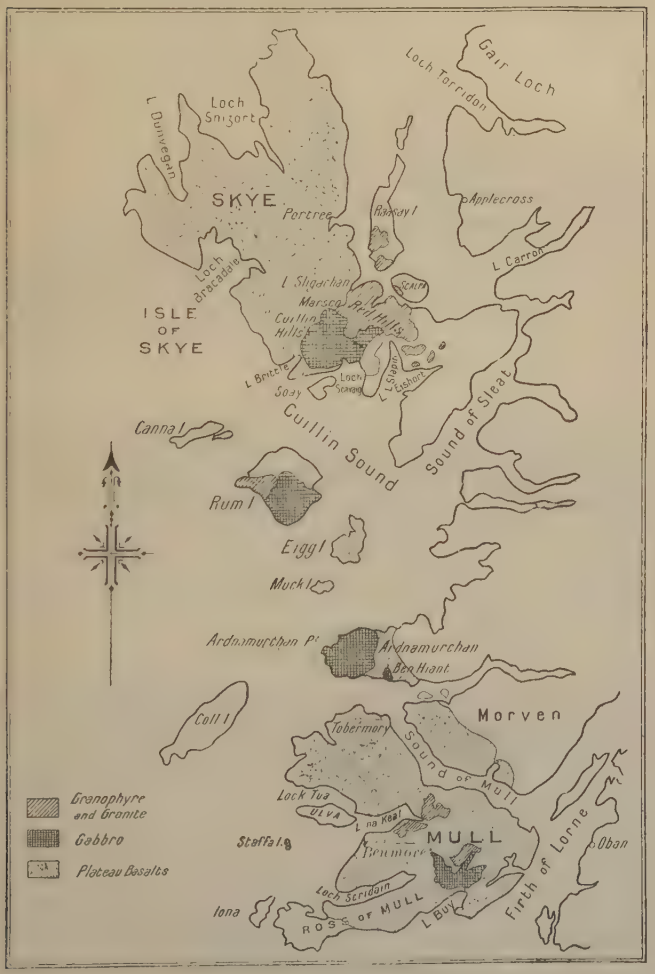

FIG. 131.

Map of the Tertiary Igneous Rocks of the Western Isles of Scotland. Scale: 1 inch = 20 miles.

The Jedburgh group, which extends to the west for a dozen miles, thins away to the east, and the two Markle series come together. It appears that a volcanic centre furnished basalts of the Markle type in the neighbourhood of Kilsyth, at a time when the shales and cementstones of the west were being laid down without volcanic emission. Then were poured forth, from vents between Dumgoyn and Fintry, basalts of the Jedburgh type; and a wide plateau built up, the base of which rests in the west upon the Spout of Ballagan sandstone, while in the east it extends on to the earlier lavas. This complex group was, in turn, covered by fresh lava-flows, chiefly of the Markle type, emitted probably from the old Kilsyth focus of vulcanicity.

The Tertiary basalts have a more marked ophitic structure than those of Carboniferous age. They occur abundantly in horizontal beds forming terraced hills in Arran, Mull, Rum, Skye, Raasay, etc. Dykes of the same rocks are abundant in Arran, Mull, Eigg, Skye, and Raasay. In numerous cases the dykes are bordered by a narrow selvage of dark-coloured glass or tachylyte.

South-West Scotland. Basic lavas of Arenig age, associated with pyroclastic rocks, occur in the neighbourhood of Ballantrae in the south-west of Ayrshire, and in the Sanquhar district of Nithsdale. They are dark green or purple rocks. There are two common types: the one compact and non-porphyritic, with small spherical amygdales, the other porphyritic, with large phenocrysts of plagioclase in a dark-green matrix. The green colour is due to the abundant

presence of chlorite, which has no doubt replaced the original augite of the groundmass. There are no phenocrysts of augite or hornblende; but the tuffs of Bail Hill, near Sanquhar, contain large crystals of these minerals, derived probably from the breaking up of a magma in which these minerals had separated out.[1] "Pillow structure" is developed both in the Ballantrae and in the Sanquhar lavas.

Olivine-basalts occur among the Lower Old Red Sandstone andesitic lavas (see page 370) in the Lorne area, as at Melfort.[2]

Ireland. Basalts of Bala age are associated with andesites in the Kildare inlier (see p. 370) at Grange Hill and the Hill of Allen. They constitute a porphyritic type containing phenocrysts of labradorite in a groundmass of felspar needles, augite and magnetite. Some serpentinous matter possibly represents olivine.[3] Carboniferous olivine-basalts occur in the Limerick district of the south-west of Ireland. Watts describes them as consisting of granular augite and magnetite set in a more or less devitrified glass, with microlites of felspar and porphyritic plagioclase, serpentinized olivine, and some well-marked augite.[4]

The Tertiary basalts of Antrim belong to the same petrographical province as the Western Isles of

[1] Teall: Silurian Rocks of Scotland, *Mem. Geol. Surv.*, vol. i., 1899, p. 84.

[2] *Summary of Progress*, *Geol. Surv.*, 1902, p. 27.

[3] Reynolds and Gardiner: *Quart. Journ. Geol. Soc.*, vol. liii., 1896, p. 287.

[4] Watts: Guide to the Collection of Rocks, etc., *Geol. Surv. Ireland*, 1895, pp. 93 and 94.

Scotland, and the rocks show no distinctive features. There were two epochs of eruption, both in Eocene times. The upper basalts are separated from the lower by a red lateritic zone derived from the decay of the lower basalts. The volcanic sheets afford in places magnificent examples of columnar structure, as at the famous Giant's Causeway.

Isle of Man. Porphyritic olivine-basalts of Carboniferous age form the Stack of Scarlet, on the south coast of the Isle of Man. They are decomposed rocks consisting of phenocrysts of plagioclase in a groundmass of felspar needles, together with chlorite, calcite, and abundant iron-ore. Olivine is represented by chlorite replacements.[1]

DISTRIBUTION OF ALKALI-BASALTS.

Basic volcanic rocks with a felspathoid constituent have scarcely been recorded in the British Isles; but Prior has described an analcime-bearing basalt from Rathjordan in County Limerick. This rock, which is probably a leucite-basalt in which the leucite has been changed to analcime, occurs as a lava interbedded with tuffs.[2]

DISTRIBUTION OF LIMBURGITES.

Limburgites have been described from the Whitelaw Hill, Haddingtonshire[3] (see p. 351); and from the necks or volcanic necks of Eastern Fife, as at Lath-

[1] Geology of the Isle of Man, *Mem. Geol. Surv.*, 1900, p. 324; and Hobson: *Quart. Journ. Geol. Soc.*, vol. xlvii., 1891, p. 441.

[2] G. T. Prior: *Min. Mag.*, vol. xv. (1910), p. 315.

[3] Hatch: *Trans. Roy. Soc. Edin.* vol. xxxvii., 1892, p. 116.

allan, near Largo, at Elie Ness, and at Dunino, 4 miles south-east of St. Andrews.[1]

In Ireland limburgite lavas of Carboniferous age have been described in the Limerick area, as at Nicker Hill; and Knockseefin. The type consists of phenocrysts of augite and olivine set in a plexus of augite microlites.[2] The silica percentage is 38. Similar rocks have also been described from Philipstown, Queen's County.[3]

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[1] Flett and Seymour: Geology of East Fife, *Mem. Geol. Surv.*, 1902, pp. 399-403.

[2] Watts: Guide, etc., *Geol. Surv., Ireland*, p. 94.

[3] Watts: Guide, etc., *Geol. Surv., Ireland*, p. 38.

APPENDIX

TABLE FOR THE DETERMINATION OF THE CHIEF MINERALS OF IGNEOUS ROCKS IN THIN SECTION.

By R. H. RASTALL and J. ROMANES.

EXPLANATION OF TABLE.

Method of Working.—Starting with division 1, two alternatives present themselves. Opposite each is a number referring to a subsequent division. Select the alternative suitable to the mineral under observation, and proceed to the division corresponding to the reference number, where other sub-divisions will be found. Repeat the process until the name of the mineral sought is ultimately reached. The bi-refringence is expressed as "very strong," "strong," "moderate," and "weak"; the following minerals being typical for each division:—[1]

Very Strong (above ·04)	Calcite. Zircon. Muscovite.	*Moderate* (·007—·015)	Hypersthene. Quartz. Orthoclase.
Strong (·015—·04)	Olivine. Augite Hornblende.	*Weak* (below ·007)	Nepheline. Apatite. Chlorite.

[1] See page 80 for an explanation of these expressions.

Divisions.		*Reference Number*
1.	Colourless	2.
	Coloured	13.
2.	Isotropic	3.
	Doubly refracting	4.
3.	Refractive index, very high	**Garnet.**
	Refractive index, very low; occasionally faintly blue; *in intermediate rocks*	**Sodalite.**
	Refractive index, very low; *in basic rocks*	**Analcime.**
	Refractive index, very low; polygonal crystals with zonary structure	**Nosean.**
4.	Double refraction, very strong	5.
	„ „ strong	6.
	„ „ moderate	7.
	„ „ weak	11.
5.	No cleavage; prismatic form; refractive index, very high; crystals usually small	**Zircon.**
	One cleavage; refractive index, moderate	**Muscovite.**
	Fine cleavage lines intersecting at an acute angle; refractive index, variable, according to position of section	**Calcite.**
6.	Usually in rounded grains; no cleavage; conspicuous irregular cracks; refractive index, high	**Olivine.**
	Extinction oblique, maximum 38°	**Diopside.**
	„ „ „ 15°	**Tremolite.**

Divisions.		*Reference Number.*
7.	Refractive index, high	**Enstatite.**
	„ „ low	8.
8.	Mesh or bladed structure	**Serpentine.**
	Cross-hatched twinning	**Microcline.**
	Lamellar twinning	9.
	„ „ , confined to lenticular patches	**Perthite.**
	Carlsbad twin or none	**Orthoclase.**
	Water clear, no twins	**Quartz.**
9.	Maximum extinction angle 6°-20°	10.
	„ „ less than 6°	**Oligoclase.**
	„ „ 20°-35°	**Labradorite.**
	„ „ over 35°	**Anorthite**
10.	Refractive index lower than that of quartz	**Albite.**
	Refractive index higher than that of quartz	**Andesine.**
11.	Refractive index high; hexagonal prisms; transverse cracks; extinction straight	**Apatite.**
	Refractive index high; lath-shaped sections, with striations or peg-structure	**Melilite.**
	Refractive index low	12.
12.	No twins; often lines of bright inclusions	**Nepheline.**
	Rounded crystals, often with complex twinning	**Leucite.**

Divisions.		*Reference Number.*
13.	Opaque	14.
	Transparent	15.
14.	Black, silvery by reflected light	Magnetite. Ilmenite.
	Yellow by reflected light	Iron Pyrites.
15.	Isotropic; brown	Melanite Garnet.
	„ ; pink	Pyrope Garnet
	„ ; green	Pleonaste Spinel.
	„ ; traces of pale blue	Haüyne.
	Doubly refracting	16.
16.	Double refraction very strong	17.
	„ „ strong	18.
	„ „ moderate	19.
	„ „ weak; colour very pale green	Chlorite.
17.	Brown; pleochroism weak; small diamond-shaped crystals; extinction straight	Sphene.
	Brown or green; pleochroism strong; one cleavage; extinction straight	Biotite.
	Yellow; weak pleochroism; extinction straight	Epidote.
18.	No cleavage; colour blue or brown; pleochroic; extinction straight	Tourmaline.
	Two cleavages at 124°; pleochroic	20.
	„ „ „ 87°	21.
	One cleavage only visible; refractive index high	22.

Divisions.		*Reference Number.*
19.	Refractive index high; pleochroism slight, in green and pink; extinction straight	**Hypersthene.**
	Refractive index low; colour very pale green	**Serpentine.**
20.	Brown or green	**Hornblende.**
	Light blue	**Arfvedsonite.**
	Deep blue	**Riebeckite.**
21.	Pale green, pale brown or purplish brown	**Augite.**
	Emerald green; slightly pleochroic	**Ægirine.**
22.	Maximum extinction angle not more than 24°; brown, green or blue; pleochroic	23.
	Maximum extinction angle 45°; pale brown or green; not pleochroic	**Augite.**
	Maximum extinction angle 5°; emerald green	**Ægirine.**
	Extinction straight	**Hypersthene.**
23.	Maximum extinction angle 20° to 24°; brown or green	**Hornblende.**
	Maximum extinction angle 14°; pale blue	**Arfvedsonite.**
	Maximum extinction angle 6°; deep blue	**Riebeckite.**

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